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Exploitation of Smart Materials and Sensors as Disruptive Technologies

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ABSTRACT

Smart materials and sensor systems have made incremental advances across a broad set of Defence-related activities as materials technology continues to be developed, and a greater understanding of the underlying science gained. There is the potential for materials and sensor systems to be combined to effect a technological advantage for the Australian Defence Force in the military domain when exploited. This paper discusses the potential of these materials and systems to affect these changes, and addresses the expected future directions of the technology and systems research areas in the Advanced Materials and Sensor Systems Branch (AMSS) within Maritime Platforms Division (MPD) and the Defence Science and Technology Organisation (DSTO) as a whole. It will also provide guidance for the forward research program.

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Exploitation of Smart Materials and Sensors as Disruptive Technologies

Executive Summary

Research into advanced materials, sensors, and systems has yielded many unusual and exciting results over the past half-century. The synthesis and engineering of material properties from the nano- to the macro-scale has resulted in the discovery or development of advantageous chemical, physical, and mechanical properties, with smart materials able to respond repeatably to stimuli under a range of conditions. This has led to the potential for automatic decision-making at a molecular level, and exposed a broad sphere of potential application for existing material structures. Combined with modern micro- and nanoelectronics, there is the potential for technological disruption to occur in military materials technology, whereby the decision maker, war fighter, and platform maintainer gain a distinct advantage.

This review defines disruptive technology and discusses the ways in which the Maritime Platforms Division (MPD) and Defence Science and Technology Organisation (DSTO) can be best prepared to exploit its future advent, providing specific recommendations for the forward direction of Long-Range Research (LRR), without attempting to pick transformational applications from current advanced materials and sensors research programs.

The status of several areas of advanced materials and sensor research is reviewed, including those in which MPD and / or DSTO operates current research programs. In order to better understand the way in which the outputs of these studies may be realised, potential data management and processing methods that transform smart systems into disruptive technologies have also been reviewed.

Contents

Abbreviations

AC	Alternating Current
ACES	ARC Centre of Excellence for Electromaterials Science
ADF	Australian Defence Force
ANSTO	Australian Nuclear Science and Technology Organisation
ARC	Australian Research Council
ASC	Australian Submarine Corporation, now ASC Pty Ltd
C4I	Command, Control, Communications, Computers, and Intelligence
CAST-CRC	CRC for Cast Metals Manufacturing
CDS	Chief Defence Scientist
CERP	Corporate Enabling Research Program
CIEAM	CRC for Integrated Engineering and Asset Management
CNT	Carbon Nanotube
CoE	Centre of Expertise
COTS	Commercial-off-the-shelf
CP	Conducting Polymer
CRC	Cooperative Research Centre
CRC-ACS	CRC for Advanced Composite Structures
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTD	Capability Technology Demonstrator
DC	Direct Current
DFCTC	Defence Future Capability Technology Centre
DM	Decision Maker
DMO	Defence Materiel Organisation
DMTC	Defence Materials Technology Centre
DSAN	Defence Science Access Network
DSTO	Defence Science and Technology Organisation
ELDP	Executive Leadership Development Program
EM	Electromagnetic
FET	Field-effect Transistor
FSS	Frequency-Selective Surface
GPSL	Graduate Program in Scientific Leadership
HPPD	Human Protection and Performance Division
IED	Improvised Explosive Device
IP	Intellectual Property
IPRI	Intelligent Polymer Research Institute
IQ	Intelligence Quota

IR	Infrared
LED	Light-emitting Diode
LMT	Logistic Model Tree
LRR	Long-range Research
MEMS	Micro-electro-mechanical-system
MOTS	Military Off-the-shelf
MPD	Maritime Platforms Division
MWNT	Multi-walled Carbon Nanotube
NASA	National Aeronautics and Space Administration
NDE	Non-destructive Evaluation
NEMS	Nano-electro-mechanical system
QWIP	Quantum-well Infrared Photodetector
R&D	Research and Development
RAAF	Royal Australian Air Force
RAM	Radar-absorbing Material
RAN	Royal Australian Navy
RCS	Radar Cross-Section
ResMan	Residential Introduction to Management
RMA	Revolution in Military Affairs
S&T	Science and Technology
SHM	Structural Health Monitoring
SMA	Shape-memory Alloy
SME	Subject Matter Expert; Small-to-Medium Enterprise
SMM	Shape-memory Material
SMP	Shape-memory Polymer
SWNT	Single-walled Carbon Nanotube
TTCP	The Technical Cooperation Program
UAV	Unmanned Aerial Vehicle

1. Introduction

This paper is one of a number of literature reviews of scientific domains, aimed at strategic planning of the Maritime Platforms Division (MPD)'s Long-Range Research (LRR) and Corporate Enabling Research Programs (CERP). A survey of the list of topics reveals several that are closely related to the topic of this materials-focused paper. These are:

- Design, fabrication and application of next generation materials including functional materials and meta materials;
- Control of degradation of materials including modelling, inspection, analysis and corrosion control techniques and tools; and
- MEMS, biotechnology and nanotechnology;

While there is necessarily some overlap between the four topics, the intention here is to avoid duplication, and to seek to address issues that are distinctly unique to this topic. At the outset, it is desirable to develop a conceptual framework for the review, to provide some bounds to the scope, while not eliminating lines of enquiry which might be ultimately beneficial.

In this context, examination of the titles of the other topics shows many are focused on the current state of the art and predictable evolutionary developments in that technology domain. This review would fall into the same category if it were titled "Smart materials and sensors". The key words of differentiation are "Exploitation" and "Disruptive Technologies". These words accentuate the requirement to not only engage in technology forecasting, but to identify those technologies that would provide a revolutionary change (and desirable advantage) in the conduct of military operations. Exploitation emphasises the need to identify mechanisms whereby such technologies, having been identified as having potential to be disruptive, can be progressed from concept or laboratory prototype to being incorporated into military equipment.

The potential scope of the topic is thus much wider than a review of current or developing smart materials and sensor technologies. The ultimate goal of the review must also be borne in mind. The intention is to inform planning of MPD's LRR program, by

- "articulating the direction and speed of the *evolution* of the science"; and
- "identifying gaps that we should be addressing".

At first there appears to be a possible disconnect between these intentions and this topic in respect to disruptive versus evolutionary technologies. There is an apparent contradiction in predicting which technologies arising from generally evolutionary development in the vast array of candidate materials and sensors will ultimately prove to be disruptive and hence worthy of exploitation through channelling of MPD's finite LRR resources.

The history of scientific and technology development allows some confidence in extrapolation of the current status through evolutionary incremental developments, and thus a basis for evolutionary technology forecasting. However, there has been little success in forecasting which fields of science or technology are likely to provide revolutionary breakthroughs that are disruptive in terms of opening up opportunities for exploitation, and that will overturn the status quo to military advantage.

"Picking winners", even when conducted with statistically significant numbers of experts in particular fields of science or technology, is unlikely to provide an enhanced success rate. A comparison of four viable technology forecasting methods has been summarised [1] and includes:

- Environmental scanning and emerging issues analysis;
- Delphi-based group consensus;
- Historical analysis; and
- Alternate futures.

This paper will not attempt to apply any rigorous approach to technology forecasting; it is a specialised field beyond the scope of this paper. However it is clear that any such approach must involve an awareness of the possible future battle space, both evolutionary and revolutionary.

The paper will summarise developments in key research areas in smart materials and sensors, and will identify likely evolutionary developments as identified by subject matter experts. The paper will address whether it is feasible to predict key areas in which disruptive technologies may occur, and how best MPD should position its LRR and CERP resources to recognise and take advantage of such developments.

1.1 What are Smart Materials, Structures and Systems?

The following definition of smart materials and structures is taken from a paper of the same name, by Cao, Cudney and Waser [2].

> *"A smart structure is a system containing multifunctional parts that can perform sensing, control, and actuation; it is a primitive analogue of a biological body. Smart materials are used to construct these smart structures, which can perform both sensing and actuation functions.*
>
> *The 'I.Q.' of smart materials is measured in terms of their 'responsiveness' to environmental stimuli and their 'agility.' The first criterion requires a large amplitude change, whereas the second assigns faster response materials with higher 'I.Q.' Commonly encountered smart materials and structures can be categorised into three different levels: (i) single-phase materials, (ii) composite materials, and (iii) smart structures. Many ferroic materials and those with one or more large anomalies associated with phase-transition phenomena belong to the first category. Functional composites are generally designed to use non-functional materials to enhance functional materials or to combine several functional materials to make a multifunctional composite. The third category is an integration of sensors, actuators, and a control system that mimics the biological body in performing many desirable functions, such as synchronisation with environmental changes, self-repair of damages, etc. These three levels cover the general definition of smart materials and structures."*

Potential linkages and dependencies between topics related to the sphere of smart materials and sensor systems were proposed by the authors, and are given in Figure 1.

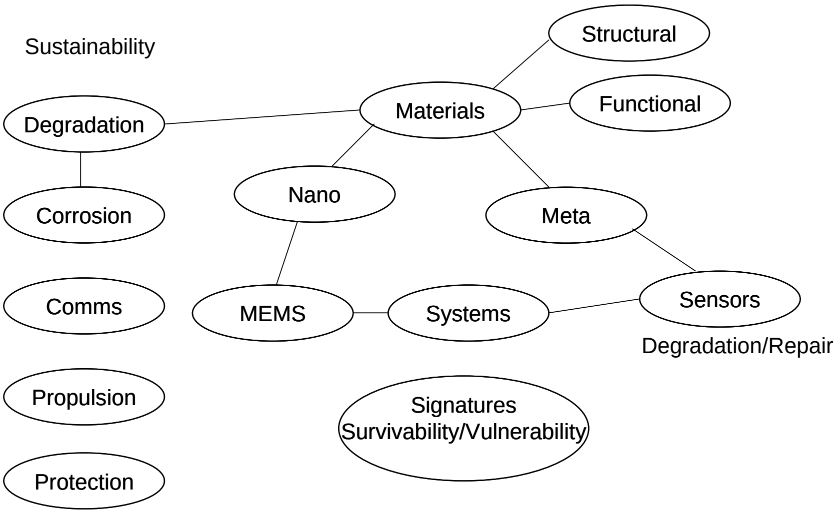

Figure 1: Mind map showing potential linkages and dependencies between topics within the sphere of smart materials and sensor systems.

These linkages and dependencies are not rigorous, but assist one to focus on the range of materials, and overlaps of interest with other review topics, such as (i) Design, fabrication and application of next generation materials, (ii) Control of degradation of materials, and (iii) MEMS, biotechnology and nanotechnology.

Figure 2 shows schematically how the "smart" integration of materials, structures, and sensors into smart structures is able to result in a Revolution in Military Affairs (RMA) [3], where its exploitation disrupts existing technology.

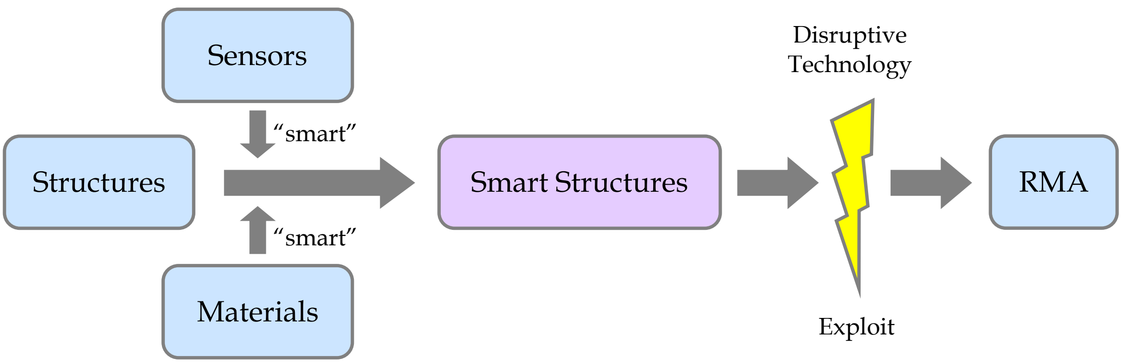

Figure 2: The development of smart structures from materials, structures, and sensors, and potential revolution in military affairs via subsequent exploitation as disruptive technology.

Figure 3 shows a hypothetical example based on the schematic in Figure 2 of the incorporation of carbon nanotubes (as both structural materials and actuators), together with fibre-optic sensors, into a multifunctional composite wing structure, achieving reactive wings. The sensors in the wings would detect stresses or vibrations, relaying signals to a local controller that would actuate the carbon nanotubes to change the wing geometry to minimise the stresses or vibrations. This could form part of an automated flight control system that might minimise buffeting or incipient stall. It might be used on manned aircraft to minimise pilot fatigue, or on unmanned aerial vehicles (UAV). If miniaturised, it might make feasible swarms

of micro-UAV requiring minimal external flight control. Such technology, if exploited would truly be disruptive and hence revolutionary in military application.

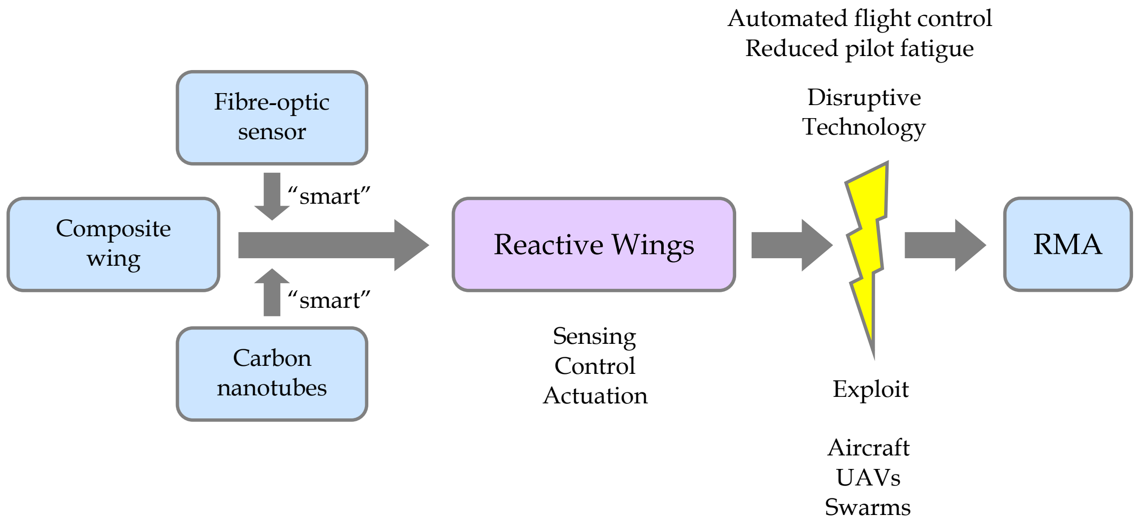

Figure 3: Hypothetical example of technology disruption due to the smart insertion of fundamental materials systems, resulting in a smart multifunctional composite structure.

1.2 Smart Materials IQ

In accordance with the above concept of a smart materials "IQ", a hierarchy can be invoked. Passively smart materials respond to external change without assistance, whereas actively smart materials utilise feedback loops enabling them both to recognise the change and to initiate an appropriate response through an actuator circuit [4]. Materials which retain information from previous stimulus and adapt their response upon subsequent stimulus may be considered to display a "learning" mode.

1.3 Elements of a Smart System

By analogy with electronic systems, a number of functional elements need to be integrated in order to construct a smart material system. These include a sensor material that responds to a particular environmental stimulus. When suitably coupled with an actuator, sometimes collocated, via a feedback controller, a response is made by the actuator that is proportional to the stimulus. Electronic proportional-integral-derivative controllers are used widely in industrial control systems, providing a generic control loop feedback mechanism. A processor allows external control of the controller, data-logging, trend analysis and "learning". Microprocessors now combine both controller and processor in one small package.

A smart material system may similarly combine two or more elements. For instance, a magnetostrictive material integrated with a piezoelectric material can produce a large magnetoelectric effect. The multifunctional composite, with combined sensor and actuator functions, acts as a good magnetic probe. The electric output can be used to initiate a desired response via either a controller, or another suitable actuator.

1.4 Disruptive Technologies

The term *disruptive technology* was first used by C. M. Christensen [5].

A definition provided by *Nanotechnology Now,* is

> *"Any new technology that is significantly cheaper than current, and/or is much higher performing, and/or has greater functionality, and/or is more convenient to use. It will revolutionise worldwide markets by superseding existing technologies. "Paradigm shifting" is a well-worn connotation. Although the term may sound negative to some, it is in fact neutral. It is only negative to organisations that are unprepared for change, and fail to adapt, only to fall behind, and ultimately disappear. The results are not just evolutionary, they are revolutionary. Companies will go out of business because a new competitor emerges, just as the advent of the zipper eradicated so much of the button industry, the vacuum cleaner decimated the broom industry, and the personal computer wiped out the typewriter." [6]*

An alternative definition of Disruptive Technology follows:

> *"This term was coined by Clayton M. Christensen to describe a new, low-cost, often simpler technology that displaces an existing sustaining technology. Disruptive technologies are usually initially inferior to the technology that they displace, but their low cost creates a market that induces technological and economic network effects that provide the incentive to enhance them to match and surpass the previous technology. They create new industries, but eventually change the world. Examples include the internal combustion engine, transistors and the Internet." [7,8]*

To understand the impact of disruptive technology it is useful to consider the nature of how the trends in innovation and technology uptake occur. As an example one can look at the way in which the materials employed in various aircraft structures have developed since the fabrication of the earliest aircraft. Figure 4, compiles information from a variety of sources to illustrate a steady increase in the usage of titanium and composite materials since the 1980s, after an approximately 30 year period of dominance by aluminium alloys. While the enduring need to reduce aircraft weight has been a significant driver in the introduction of newer materials, the initial impetus was a need for greater corrosion resistance on aircraft carrier-based combat planes such as the F/A-18.

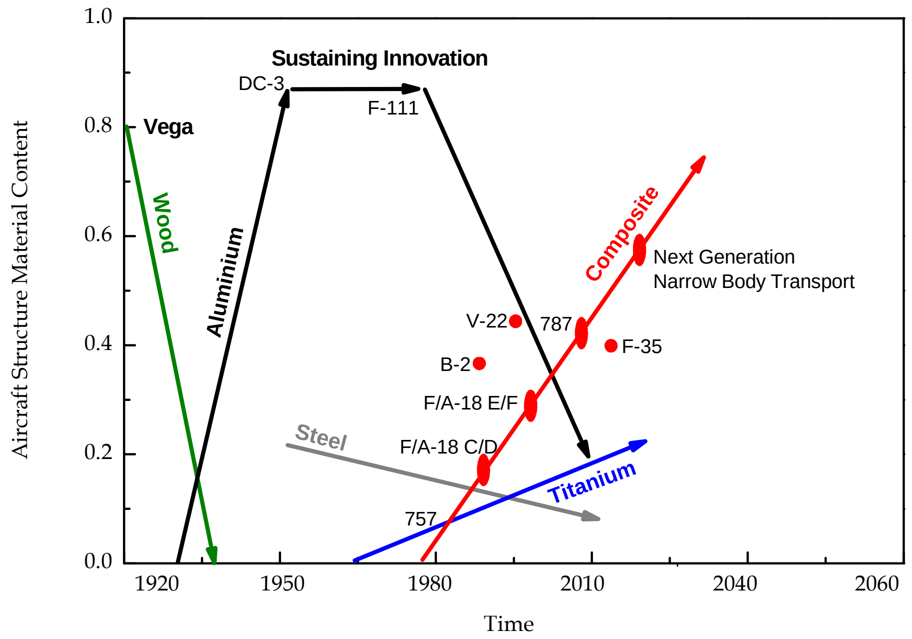

Figure 4: Changing relative use of materials in aircraft structures by weight over time.

In terms of technology development, this shift in usage has resulted in a need for new work on design and manufacture of composites, while sustaining technologies for aluminium structures remained in high demand. Currently, a shift towards greater inspection and maintenance of composite structures is occurring, together with work on high-volume machining technologies for titanium. During the past several decades there has been a vast increase in investment in carbon fibre production, with capacity doubling every 2–3 years.

While the preceding example allows for numerous observations to be made regarding technology trends, it is worth noting that it has taken the aircraft industry approximately 30 years to perform a large scale technology change. This industry is highly regulated, resulting in a length and expensive qualification process for new structural materials. In less regulated and possibly more dynamic industries, change can occur on a shorter timeframe, in areas such as consumer electronics, in which major technology disruption can occur on as short as a 3 year timescale. Technology changes for some applications will therefore be easier to forecast than for others, due to factors that are initially secondary to the pure development of materials technology. Another applicable factor in the early development of aircraft composites was their high cost per kg, and a general perception of inferior performance to the existing aluminium design. However, the reasons for which carbon fibre composites were initially adopted in combat aircraft drove the technology towards improved competitiveness for broader applications. Finally, it should be noted that the major underlying drivers for improved aircraft structure have not changed greatly during this period; improved aircraft performance and economy without reducing safety, durability, and cost-effectiveness.

The above example has discussed the replacement of existing technology, which may be viewed as having been disruptive at the end of a timeframe depending on a range of factors. The more abrupt type of technological disruption and displacement occurs whereby revolutionary innovation that allows capability that has been previously either unavailable, or

unattainable through (for example) prohibitive expense. However, the technology disruption is only considered to have occurred where the revolutionary innovation displaces the existing technology.

1.5 Exploitation in the Civilian and Defence Domains

Exploitation, "to make good use of (a resource)" [9] is the definition most clearly applicable to this topic. The alternate definition of exploitation (to make use of unfairly; benefit unjustly from the work of) appears at first to be not applicable in this case. However, in the military, as in commerce, one cannot presume that one's adversary or competitor will not exploit in both senses of the word. Indeed, a ruthless adversary or competitor will seek to maximise the element of surprise, and to capitalise on their opponent's weaknesses.

This is consistent with the concept of "asymmetric warfare", defined by *Wikipedia* as:

> *"Asymmetric warfare originally referred to war between two or more belligerents whose relative military power differs significantly. Contemporary military thinkers tend to broaden this to include asymmetry of strategy or tactics; today "asymmetric warfare" can describe a conflict in which the resources of two belligerents differ in essence and in the struggle, interact and attempt to exploit each other's characteristic weaknesses. Such struggles often involve strategies and tactics of unconventional warfare, the "weaker" combatants attempting to use strategy to offset deficiencies in quantity or quality. Such strategies may not necessarily be militarised. This is in contrast to symmetric warfare, where two powers have similar military power and resources and rely on tactics that are similar overall, differing only in details and execution." [10]*

Asymmetric warfare can be used by "weaker" combatants to counter the advantage of RMA, where the "stronger" opponent has superior military power, resources, information systems, and ability to respond to conventional threats.

The use of Improvised Explosive Devices (IEDs) by non-state combatants such as terrorists is an example of exploitation (in both senses) of disruptive technology, and is a form of asymmetric warfare. Using a wide range of conventional and unconventional triggering devices, incorporating locally available, cheap and improvised technology, the "weaker" combatant can improvise IEDs from readily available munitions and explosives. With strategic placement, IEDs kill, injure, destroy assets, limit the mobility of and demoralise opponents, at relatively low risk to the perpetrator, thus achieving a significant advantage disproportionate to their cost. The large effort currently applied by the international allied forces to countering IEDs illustrates the magnitude of the response required to reduce their effectiveness.

Therefore the topic *Exploitation of Smart Materials and Sensors as Disruptive Technologies* needs to be examined not only from the viewpoint of the Defence Science and Technology Organisation (DSTO) seeking to maximise advantage for the ADF, but also from the viewpoint of an opponent (either military or terrorist), who may "exploit" a technology in order to achieve their objectives. The smart materials and sensors focus for the two different perspectives is likely to be quite different. The main DSTO focus should be awareness of developments in smart materials and sensors that enable new applications that will confer an advantage to the ADF. However, an opponent may also exploit cheap, commercial-off-the-

shelf (COTS) technology and apply it in a revolutionary way to achieve a capability that provides a disruptive advantage. DSTO needs to anticipate such possibilities in order to be able to provide countermeasures in a sufficiently short time that the opponent's advantage of surprise is blunted.

1.6 Review of Research State-of-the-art in Smart Materials and Sensors

Within this review we focussed on four areas selected to represent a wide cross-section of the broad coverage of smart materials and sensors. These are contained within Sections 2–5 of this paper, and are:

- Shape memory/change materials, encompassing both metallic alloys and polymeric materials;
- Smart sensing and self-healing, selected due to the significant interest in this area by MPD over some years;
- Sensors and sensor systems, broadening the scope from the platform-centric focus of much sensor work currently undertaken within MPD; and
- Electromagnetic signature management, selected due to the bulk of research performed in this area by MPD, and its increasing significance to the ADF and future platform acquisition programs.

Data management and processing is reviewed in Section 6, and is considered an area of significance due to the increasing automation of systems, and necessity of its role in fully realising the advantages of smart materials and sensors.

We attempted to avoid duplication with the areas of MEMS and biotechnology which are the subject of another review, however there is some overlap in the nanotechnology area, and with the review on meta-materials and advanced metals and fabrication techniques.

Current external linkages are identified, and recommendations made where these should be strengthened or new linkages established.

The culture of an organisation must also be considered when recruiting individuals or forming research teams, so that the potential for innovation is maximised. Recommendations are made for organisational changes in MPD which might achieve synergies between talented individuals and teams, with a mix of personal, science and technology, and corporate skill sets that would increase the likelihood of effective exploitation of disruptive technological advances in a particular LRR field.

2. Shape Memory/Change Materials and Smart Systems

2.1 Introduction

The discovery in 1962 of the shape memory effect in nickel-titanium alloys at the US Naval Ordnance Laboratory heralded a major research outcome. This was followed in 1971 by the first major military application of shape-memory alloys (SMA) in the F–14A aircraft as hydraulic couplings [11]. Today the unique property of shape-memory materials (SMM) to change shape and return to their original pre-deformation dimensions continues to be a topic of intense interest with over 4000 patents filed since 2003 and many more scientific articles published on SMA. NiTi-based alloys remain the major commercially available SMA, with current work aimed at new NiTi–X (X = Fe, Nb, Cu) alloys to further extend their range of properties and potential applications. Shape memory materials research, however, has expanded beyond its traditional metallic-base roots into exploring shape-change and actuation properties of new polymeric and hybrid composite structures where the potential exist to develop a range of new applications, in particular light weight "flexible" structures.

A broad range of commercial applications have been developed for SMA beyond their "simple" shape-change ability through decades of fundamental research into the microstructural mechanisms responsible for the evolution of shape-recovery. Current applications reported for SMM, both metallic and polymeric include: actuators [12-14], robotic prosthetics [15], noise and vibration control systems [16,17] fibre reinforcement [18,19], couplings and fasteners [20], and SHM (structural health monitoring) systems [21]. From a Defence perspective, much of the current research and development into SMM has direct relevance to potential applications for military platforms. Further, it can be envisaged that SMM will increasingly become an integral part of smart systems adopted for defence applications, owing to their many active and passive sensing and actuation properties.

2.2 The Shape Memory Mechanism

SMA are predisposed to exist in either of two crystallographic variations (phases), referred to as Austenite (A) and Martensite (M), named after the high and low temperature phases respectively in the iron-carbon phase system. The phase transformation in SMA from A to M upon cooling, and vice-versa for heating, is a rapid, diffusionless transformation that importantly is temperature- and not time-dependent. Furthermore, the transformation temperature may be actively manipulated through changes made in the alloy composition and specific heat treatment procedures. Typically the microstructure of SMA consist of needle-like platelets of twinned martensite, in response to the crystallographic changes associated with the A to M phase transformation. Shape recovery arises from the ability of the twinned martensite to accommodate low levels of strain (~10%) without generation of dislocations and the onset of permanent deformation. Hence "deformation" induced in the martensitic state maybe recovered through heating the alloy to initiate the reverse M to A transformation, which results in a return of the component to its original shape that is subsequently maintained upon cooling.

For polymeric systems the shape memory or change property may arise via several mechanisms: (i) through the selection of polymers that change volume due to specific

chemical interactions or changes in solution acidity (pH) [22] or (ii) the tailoring of specific copolymer blends that consist of both soft and hard crosslinked polymer segments that possess differing glass transition temperatures. "Permanent" deformation of the copolymer is recovered by increasing the temperature of the system by heating via external source or internal methods. For example, embedded wires or conducting carbon nanotubes may be used to affect heating and the recovery of the polymer to its original hard polymer skeleton structure. Enhancements to the total recoverable strain of the polymer maybe furthered by changes to the molecular (crystallographic) orientation within the copolymer. This may be achieved via wet or melt spinning fibre fabrication techniques [23-25], together with changes to the fraction of soft and hard segments within the blend.

2.3 Shape Memory Alloys

The main SMA alloy compositions of commercial interest include: nickel-titanium-based alloys (NiTi–X, X = Fe, Nb, or Cu), the copper-based alloys CuAlNi, CuZnAl, CuAlBe and iron-based materials (FeNi–X). Ni-Ti alloys are of special significance due to their high strength, excellent corrosion resistance, high electrical resistivity, biocompatibility and large recoverable strain.

Selected papers by Van Humbeeck [17,26] provide an extensive array of applications based on the functional properties of SMA. The functional properties of SMA are broadly divided into six categories [26]:

1. *One-way SMM*. In the martensitic state, materials can be deformed up to ~8% strain and returned to their original state upon heating;
2. *Two-way SMM*. Materials that possess a "memorised" shape in both the martensitic ("cold-state") and austenitic state ("hot-state"). No external force is required to affect shape change between two desired configurations. Specialised heat treatments are necessary to obtain two way "recovery" and the long term stability of this function requires consideration, with some degradation noted with time;
3. *Applied stress*. High applied stresses may be generated through the active restriction of the material to recover its original shape upon heating;
4. *Applied force*. Recovery of the material is hindered by a counter force resulting in work performed against the external force;
5. *Super-elasticity*. In the austenitic state, materials subjected to an applied stress may undergo immediate recovery of deformation up to ~8% upon unloading. Hence large reversible deformations may be completely recovered; and
6. *High Damping*. Martensitic and two-phase materials (*A-M*) possess strong amplitude-dependent internal friction characteristics—an ability of the microstructure to dissipate energy via phase transformation and phase re-configuration dependent upon the stress environment.

2.4 Damping

2.4.1 Passive Damping Shape Memory Alloys

The *A* to *M* phase transformation which produces the observed shape memory effect in SMA is also responsible for the energy-damping characteristics. For austenitic SMA materials, mechanical energy may be dissipated through the transformation hysteresis associated with the formation of stress-induced martensite and recovery to austenite. This is in addition to the damping that arises through the shift in material elastic properties that accompany the transformation. Martensitic materials dissipate energy through the reconfiguration of the martensite domain structure developed within the microstructure. The martensite phase within the material consists of numerous domains (regions of common crystallographic orientation). Upon application of stress, the polydomain structure spontaneously reconfigures itself to accommodate the stress, in order to minimise macroscopic strain. Energy is absorbed throughout the microstructure via the internal friction associated with the movement of accommodating domains i.e. atomic displacements. Upon removal of the applied stress, the original equilibrium domain arrangement returns. Within a cyclic strain environment the polydomain structure will undergo strain accommodation and reconfiguration in accordance with the applied frequency.

The passive damping of martensitic materials is highly strain-amplitude dependent, with high damping observed at high strains (vibration levels). Thus, SMA have the ability to absorb high energy events, a property of significant military interest. A specific damping capacity of up to 40% is feasible for particular systems. The ability to harness this property requires good coupling between the structure and SMA to enable transfer of mechanical energy. The passive damping capacity of an SMA material is an intrinsic property of the material to dissipate energy. However, the microstructure maybe tailored through deformation and thermal treatments to provide peak damping performance and a particular response to the environment [17,26].

Passive damping applications for SMA include: shock wave absorption; armour material [27,28]; seismic vibration damping [29]; wires [30]; and snow skis. Alloy compositions used for passive damping applications include NiTi–X, and CuZnAl.

2.4.2 Active Damping Shape Memory Alloys

The active damping capability of SMA is harnessed through the intelligent control of the passive damping mechanisms of SMM, as described above. In addition, through the use of real-time feedback control to manage the active damping response, truly smart systems may be developed. Control of the material damping response is performed via either the thermal- or force-induced initiation of changes to the SMA martensitic or austenitic phase content and structure. The preferred method of control is by thermal activation, typically by the direct resistance heating of the material or via embedded wires in hybrid structures. Noting that the elastic modulus of the austenite and martensite structures vary widely (e.g. NiTi 800 to 200 MPa [31]) and the resonant frequency of a material is proportional to the modulus, the damping properties of a material may be tuned by external forces applied to induce specific microstructural changes. The active damping response when controlled via thermally-induced changes is, however, limited by the thermal cycle response time of the SMA, i.e. the thermal

properties of the SMA (heating and cooling rates) determine the frequency at which it may act to attain the desired damping.

SMA smart vibration control systems may be broadly classified as:

- Active strain energy tuning (strained wires);
- Active modal modification (unstrained wires); and
- Active shape control (changing shape to influence vibration).

2.4.3 Active Control Systems

SMA may be embedded or attached to other materials to produce composite or hybrid structures where the desire is to affect material properties or a structure's response through an active control system. Typically, thermal activation of the recovery mechanism in the SMA is employed to develop the required force or stress to produce the property changes within the system.

Example applications of active property control include:

- The integration of pre-strained (tension) NiTi fibres or thin films embedded into a polymer or metallic matrix. Upon thermal activation of shape recovery, the SMA fibres are caused to exert an internal compressive stress on the matrix material. The applied force changes the stiffness of the composite material, which in term shifts its resonant frequency. Hence, the resonant frequency is tuneable via variation of the induced recovery strain, noting that the process is reversible. Influencing factors include temperature, SMA volume fraction, and pre-tension strain of embedded wires or fibres [17,26].
- SMA have potential as strain sensors and as actuators for damage suppression. SMA fibres may be embedded in a polymeric matrix, and used to measure the strain in the system via the accompanying change in the SMA electrical resistance. The variation in resistance arises through the change in volume fraction of martensite and austenite within the microstructure. Recovery of the strained SMA fibre can be thermally activated as required, in order to cause fibre contraction and exertion of a compressive stress, thus suppressing further deformation of the matrix. Furthermore, the imposed compressive force will also act to reduce the matrix tensile strain and suppress crack growth [19].
- Self-repairing bolted joints: A pre-strained (compression) SMA washer is activated to maintain the integrity of a bolted joint by maintaining tension on the bolt. The bolt tension is indirectly monitored via a piezoceramic patch located nearby that systematically measures the vibration resonance of the joint. A predetermined change in resonance is used to signify a decrease in bolt tension and joint integrity (Figure 5) [32]. Resistance heating may then be applied to effect recovery/expansion of the washer and re-tension the bolt.

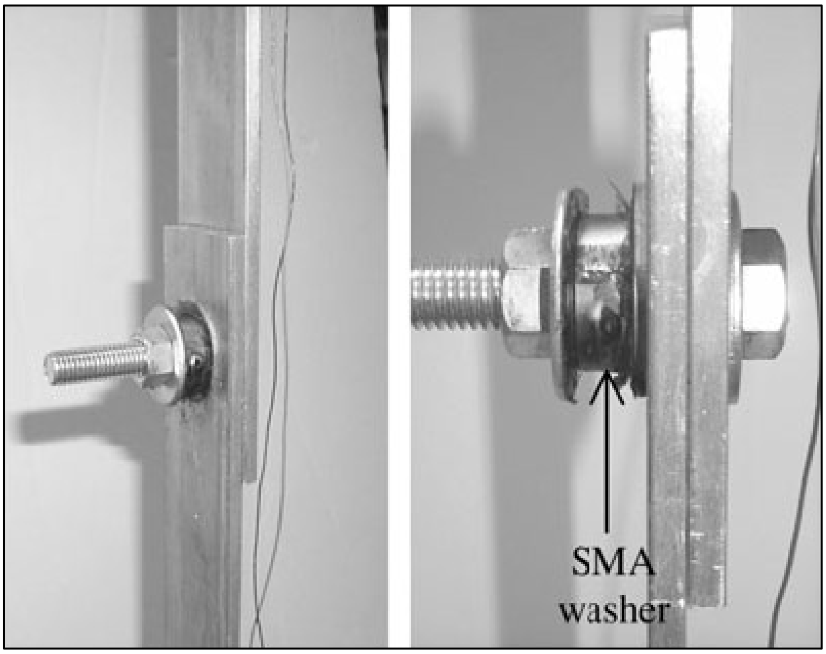

Figure 5: A self-repairing bolted joint. An active control system, consisting of SMA washer and a piezoceramic monitoring system (not shown). The SMA washer expands on demand via resistance heating, in order to increase the tension in the fastener and maintain integrity of the joint. Reproduced with permission [21].

2.5 Ferromagnetic Shape Memory Alloys (FSMA)

Intense research continues into the development of NiMnGa Heusler alloys which have the ability to undergo magnetic field-induced strain at constant temperature [33]. Strains of 6-10% have been reported for alloys in the presence of magnetic fields. The ability to induce strain is dependent on the development of a specific martensitic microstructure within the alloy that is, in turn, temperature dependent. The goal of current research is to increase the useful temperature range of such alloys by tailoring the microstructure, and also to improve fabrication processes, allowing for bulk production. Furthermore, the preparation of suitable FSMA thin films and ribbons for insertion in composite structures is foreseen as a significant future role.

Ferromagnetic alloys have the advantage of rapid actuation compared to standard thermal activated SMA. Actuation frequencies of 500 Hz with up to 6% strain are possible for NiMnGa alloys for a magnetic field of less than 800 kA/m [34]. Areas for FSMA use are envisaged to be similar to conventional SMA although they are well suited for cryogenic applications, fuel, and hydraulic systems or where rapid response is required, e.g. valve actuation. The *Defence Research and Development Canada–Atlantic* organisation has had a strong interest in magnetic shape memory materials [35-46].

2.6 Polymeric Shape Memory Materials

Shape-memory polymers based on polyurethane were initially developed in 1984 [47]. The shape-recovery response is typically induced via direct heating of the polymer, although thermal activation of recovery can occur via magnetic or electrical changes, through the incorporation of appropriate fillers. SM-polymeric (SMP) materials are typified by a structure that consists of series of "hard" (rigid) and "soft" (deformable) segments (i.e. a multi-block copolymer). The hard cross-linked segments define the equilibrium shape of the polymer or composite structure. Soft segments allow flexibility within the structure and undergo deformation on loading. They ultimately recover their original shape upon reheating to the switching temperature T_s which is equal to the glass-transition temperature (T_g), hence the difference in softening temperature (T_g) between segments is responsible for the shape-recovery [31,47] (Figure 6). The polymer soft segment can be either amorphous or crystalline, and cross-linking with the rigid segment can be either physical or chemical, each of these displaying particular advantages, as outlined by Ratna in a recent review [47].

Physical cross-linked SMP with amorphous segments include a wide range of commercially available proprietary *Mitsubishi* polyurethane materials (e.g. DiAPLEX®). The recovery temperature of available urethanes ranges from –30 to 100°C, tailored through changes in the polymer compounds and volume fraction. Crystalline soft-segment SMP systems crystallise below $T_s = T_g$ and have a well defined and narrow recovery transition range compared to amorphous segments. Such polymers are believed to store greater elastic energy. However, together with crystallinity comes a range of issues, including preferred orientation, relaxation, and other factors affecting the amorphous-crystalline phase change and melting temperature. A potential drawback of SMPs is their lack of long-term stability associated with water vapour permeability and its effect on T_s due to the weakening of hydrogen bonding between specific functional groups.

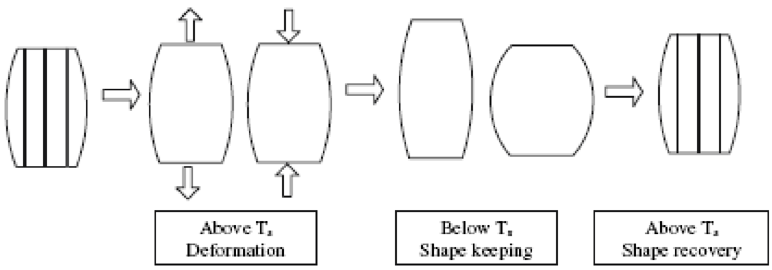

Figure 6: Schematic representation of the shape memory process. The initially two-phase polymer is deformed to the required shape above T_s via tensile or compressive stress. Upon cooling below T_s, the deformed shape is retained. Reheating to above T_s results in recovery of the polymer to its original dimensions. Reproduced with permission [47].

Light induced SMPs have been developed through the addition of compounds that develop photo-reversible cross-linking. The cross-links are caused to form and reversed by exposure to different wavelengths of light. Such SMPs eliminate the requirement for thermally-induced recovery and hence show great promise for ambient temperature shape-changing.

From a functionality perspective, the low strength and stiffness of SMPs limit their structural application, since low recovery forces are developed. Composite SMPs have been investigated, with reinforcement by incorporation of glass fibres, carbon nanotubes, and silicon carbide, to increase the stiffness of the polymer and the recovery stress achievable for applications such as actuators. Filling of polymers (polyurethanes) with carbon nanotubes can also be used to impart electrical conductivity, and hence heating by electrical resistance to enable recovery and actuation properties. Biocompatibility allows applications such as biomedical coil implants, as well as actuators on micro-air vehicles, and lightweight morphing structures. Challenges include improving durability and actuation response time, achieving one-way actuation, and increasing the recovery force.

2.7 Artificial Muscles

Activated polyacrynitrile fibres have been shown to change in length and diameter by over 100% with exposure to caustic (alkali) and acidic solutions. In acidic solutions the fibres contract, and in alkali solutions they expand. These increases in length give polymer fibres the potential to be used as actuators by varying the local pH [22]. This effect has been observed for fibres of diameter < 1 μm and length 10–50 μm.

2.8 Conducting Polymers for Artificial Muscles

When considering the different types of actuating materials available, it will become apparent that although conducting polymers may not exhibit the best combination of strain, strain rate, and stress, they do exhibit substantial operational advantages. Firstly they do not generate a large amount of heat as do shape memory alloys. Secondly, they do not require high voltages, as do dielectric elastomers, piezoelectric polymers and piezoelectric ceramics. Thirdly, they can be triggered electrically, whereas ionic gels require a chemical change. Another advantage of conducting polymers is that they are readily deposited electrochemically, allowing them to be easily incorporated onto MEMS (micro-electro-mechanical system) platforms, or they can be coagulated from solution allowing them to be formed into fibres using conventional fibre spinning technology. The enhanced performance of conducting polymers for actuators indicates that they may even rival other technologies with respect to actuation performance [48].

2.8.1 Mechanisms of Actuation in Conducting Polymers

The principal means for generating actuation in conducting polymers is through their electrochemistry. Conducting polymers are readily and reversibly oxidised and reduced without destroying their mechanical integrity. The most important aspect of the electrochemical reaction for actuation in conducting polymers is the movement of anions (A^-) into and out of the polymer. The anions are necessary to balance the positively charged polymer chains that result from oxidation of the polymer. For electro-neutrality, there must be equal numbers of positive and negative charges. The anion is sometimes referred to as the

dopant and the process of oxidation is then called *doping* [49]. Clearly the movement of anions into and out of the polymer due to redox reactions causes dimensional expansion (swelling) and contraction (de-swelling). This redox reaction can be expressed by

$$P^{+}\left(A^{-}\right)_{SOLID} \underset{-e^{-}{}_{OXIDISED}}{\overset{+e^{-}{}_{REDUCED}}{\rightleftarrows}} P^{o}{}_{SOLID} + A^{-}{}_{LIQUID} \qquad (1)$$

where P^+ is the doped (oxidised) state of the polymer and P^0 is the undoped (reduced) state. This redox reaction is valid for small anions (e.g. perchlorate (ClO_4^-), hexafluorophosphate (PF_6^-), tetrafluoroborate (BF_4^-), and chloride (Cl^-)). The polymers expand during oxidation and contract during reduction.

If the anions are bulky or polymeric anions (e.g. dodecylsulphate, dodecylbenzenesulphate, polystyrenesulphonate, and polyvinylsulphate), the redox reaction becomes:

$$P^{+}\left(A^{-}\right)_{SOLID} + M^{+}{}_{LIQUID} \underset{-e^{-}{}_{OXIDISED}}{\overset{+e^{-}{}_{REDUCED}}{\rightleftarrows}} P^{o}\left(AM\right)_{SOLID} \qquad (2)$$

where M^+ is the electrolyte cation. As the anion A^- originally incorporated in the polymer backbone during polymerisation is immobile in the redox process the movement of the electrolyte cations dominates actuation. In contrast to the redox process of Eq. (1), the polymers expand during reduction and contract during oxidation.

A great variety of performances are possible from conducting polymer actuators as a result of the many operating variables. Three main types of conducting polymer have been investigated as actuators: polypyrrole (PPy), polyaniline (PANi), and polythiophene. A virtually unlimited number of dopant anions are then available, with a simplistic view of actuation showing that the amount of actuation strain is proportional to the size of the dopant anion [50]. The movement of ions into and out of the conducting polymer and thus the expansion and contraction is also affected by the electrolyte temperature [51]. The composition of the electrolyte also has a significant bearing on the actuation performance since the electrolyte is the source of anions/cations and also must conduct electric charge (ionic charge) from anode to cathode [52]. The valency of the electrolyte cation exerts a strong influence on the actuation behaviour of the material [53].

The electrolyte also has a strong influence on the actuation behaviour. Ionic liquids, that is pure salts that have a melting temperature lower than 100°C, exhibit a stable actuation due to a wide potential window compared with normal solvent electrolytes where the breakdown of polymer and electrochemical decomposition of the solvent occur [54]. After more than 6000 cycles, the actuation strain of a PPy actuator maintains a value close to the original strain in an ionic liquid [55]. The choice of a suitable dopant and electrolyte results in a very large actuation strain, which reaches an enormous value of 40% for PPy using (nonafluorobutylsulphonyl)imide as a dopant [56].

The swelling is most probably augmented by the concomitant movement of solvent from the electrolyte into the polymer due to osmotic pressure [57]. This effect facilitates the penetration

of solvent molecules into the polymer in an amount far exceeding those bound to solvated ions. The contribution from osmotic pressure to actuation is maximised when the ionic concentration within the polymer is much larger than the ionic concentration in the electrolyte during the oxidised state, but is similar to the electrolyte in the reduced state. The presence of osmotic pressure is readily demonstrated by observing larger actuator strains for lower salt concentrations in the electrolyte.

Although an ideal actuator would require high generated stress, high generated strain, high speed of response, actuation stability, good mechanical properties, and long service life, all of these properties may not be essential simultaneously. Nevertheless, a full understanding of the actuation mechanisms is important in designing a material for particular applications. The inter-relationship of the electrical, mechanical and chemical properties of the material foreshadows the performance of the actuator (Figure 7). Therefore, the intrinsic properties of the material such as crosslinks, crystallinity, molecular alignment, porosity resulting from polymerisation conditions and type of anions should work synergistically with extrinsic conditions such as electrolyte type, concentration, operating conditions (pH, temperature), and electrical stimuli (current control, voltage control, scan rate, stimulation waveform) in order to achieve ultimate desirable performances.

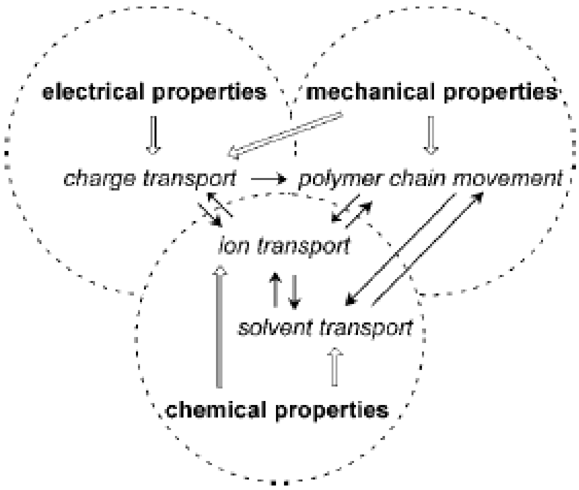

Figure 7: The inter-relationship of electrical, mechanical and chemical properties of conducting polymers. Reproduced with permission [49].

2.8.2 Robotic Fish

Wu *et al.* [58] developed a tri-layer PPy bending actuator (Figure 8) that can provide high speed displacement at its resonance frequency (e.g. Tip displacement of 2 cm at the resonance frequency of 5 Hz). Xi *et al.* [59] have investigated the effect of dopant and polymerisation conditions of PPy on force output to obtain the maximum value. Recently, a small robotic fish was designed by DSTO and the University of Wollongong using the tri-layer actuator as a tail fin propulsor [60].

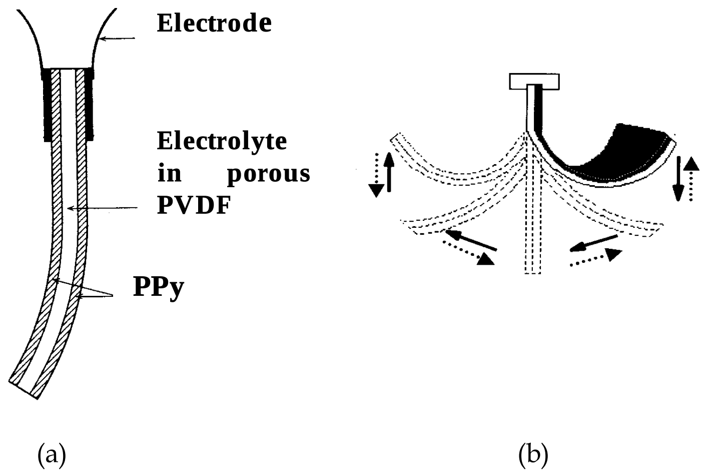

Figure 8: A tri-layer PPy actuator. (a) Structure and (b) schematic of actuator in action.

2.9 Discussion

The multifunctional properties of SMM guarantees that Defence platforms will have such materials incorporated into their structures or integrated systems in the near future. The first application of shape memory alloys in a military context has been fasteners and connectors with few applications related to actuation, sensing and smart systems. Although SMA still have a potential role in this area, the future of SMA would appear to lie in condition monitoring (sensors), active noise/vibration control, and self healing materials. The complex microstructural requirements and tailoring of composition preclude MPD from actively pursuing alloy and metallurgical development of candidate materials in isolation. Strong input and leadership by an academic provider is necessary to have an impact in this area, although off-the-shelf systems could possibly be manipulated (tweaked) by DSTO to fulfil Defence requirements as a first stage of insertion and proof testing the applicability of various SMA technologies in platforms. Nevertheless, it is expected that dedicated systems developed for defence purposes will be "available" for direct adoption, hence knowledge of the potential advantages and limitations of such technology is necessary to be on-hand should such an option be taken-up.

A number of questions remain regarding the long-term stability of SMM. This is particularly relevant to Defence platforms where materials may be required to operate for extended periods between maintenance and upwards of 15 years total duration. Uncertainties include: the long term thermal cycling and temperature excursion response of actuators and sensors, mechanical fatigue properties of actuation (high and low frequency), and the potential "ageing" of the complex microstructures.

High expectations exist for polymeric SMM due to the weight advantages of polymer materials and the potential for morphing structures and actuation, areas of significant interest for ultra-light and micro-air vehicles. However, in common with alloy systems challenges exist regarding the long-term properties of polymeric-based SM systems. These issues include: the effect of moisture permeability, reliability of recovery temperature, and repeatability of strain response.

2.10 Recommendations

Near-term investigations should be in fundamental studies of SMA materials in order to build up expertise in microstructural characterisation and measurement of physical properties associated with potential platform applications, such as temperature, time (thermal stability), deformation, and strain rate. A potential focus point for initial Defence applications is damage-tolerant structures. Consideration should also be given to industry interactions through extension to the Defence Materials Technology Centre (DMTC) maritime platforms program. Other areas of interest would be in morphing/actuation, development of armour materials, and noise and vibration damping.

3. Smart Materials and Structures for Sensing and Self-healing

3.1 Introduction

Smart materials based on organic materials such as conducting polymers (CP) and carbon nanotubes (CNT) that have been developed in the last three decades have seen a rapid take-up for many applications. Smart structures such as surfaces with organic or inorganic nanowires or nanofibres, quantum dots of inorganic and organic semiconducting materials have been produced in the past 10 years. Organic smart structures have been investigated for electromagnetic phenomena and quantum effects, and extended to the mechanical arena, in which self-healing structures, damping, and blast-mitigating structures that can provide enhanced survivability for Defence platforms have been studied.

The application of synthetic chemistry and nanotechnology has developed smart materials and structures that are selectively sensitive to external stimuli such as EM waves and mechanical changes, and respond with enhanced performance through modified electrical, chemical, and optical properties.

This section has identified areas including electromagnetic (e.g. IR) sensors, chemical sensors, biosensors, and related nanoparticles, nanostructured materials, molecular electronics, and molecular devices/machines. Self-healing polymeric composites are briefly discussed as an example of smart mechanical systems.

3.2 Conducting Polymer Electromagnetic Response

The change in complex permittivity and thus AC conductivity of CPs under microwave radiation leads to the application of radar absorption and electromagnetic interference shielding [61,62]. Switchable conductivity enables CPs to behave as a “smart” radar window [63]. Recent research on the CP electrochromic “chameleon effect” in the visible, IR and microwave regions has explored the response of CPs to electromagnetic waves for battlefield camouflage [64].

The increase in conductivity with increasing temperature in semiconductors is well-established. This effect has been applied to the construction of uncooled silicon-based bolometers [65], and a thin heat-sensitive film of vanadium oxide (VO_2) has been used in microbolometer arrays [66]. However, the manufacturing of these inorganic materials is usually costly. Recently, the effect of IR radiation on the change in resistance of CPs (poly(3,4–ethylene dioxythiophene), doped with polystyrene sulphonate, was studied using a pulsed laser IR source [67]. The responsiveness of CPs to IR radiation can be implemented to develop inexpensive IR absorbers and sensors [64]. Carbon nanotubes (CNT) also demonstrate an IR photo-response. The conductivity of a composite containing 5% single-walled carbon nanotubes (SWNT) in polycarbonate was seen to change under IR irradiation [68].

Quantum confinement in semiconductor nanostructures enables the design of novel sensing devices for electromagnetic stimuli. Quantum dots embedded in a host material by molecular

beam epitaxy is one approach used to generate quantum confinement. If the host material has a large band gap, the quantum dots form isolated potential quantum wells exhibiting several discrete energy level like isolated atoms. One of the effects exhibited by quantum wells is a strong IR absorption that occurs when electrons in the ground state of the well are excited to a higher energy level. This has been used to make quantum-well infrared photodetectors (QWIP). QWIP arrays are the fundamental element in high-performance uncooled thermal imaging systems. The *Jet Propulsion Laboratory* and *NASA* pioneered the QWIP based on GaAs/AlGaAs focal plane arrays [69]. Another example is an InGaAs/InGaP quantum dot infrared photodetector, characterised by high sensitivity in the mid- and far-IR bands [70].

3.3 Chemical Sensors and Biosensors

Chemical sensors and biosensors can be fabricated in a number of ways, including:

- Coating the sensing materials on a substrate between two electrodes;
- Coating a macro- or micro-electrode with the sensing materials by electrochemical methods; and
- Field-effect transistors using the sensing materials as active materials.

3.3.1 CNT-based Conductance/Capacitance/Electrochemical Sensors

There exists a need in Defence for small, sensitive rapid-response sensors for the detection of toxic chemicals, nerve gas, viruses, and biomolecules, for applications such as personnel protection and monitoring of submarine atmospheres. CNT-based sensors are emerging as a significant field for this purpose. SWNT network-based transducers rapidly and reversibly respond to a wide spectrum of chemical vapours, with concentrations as low as parts-per-billion in some cases. They also exhibit an incredible potential surface area per unit mass, estimated to be as high as 1600 m^2/g.

Sensors for chemical vapour detection based on the change of conductance or capacitance of SWNT have been fabricated and tested [71,72]. While the dielectric effect of the molecular absorbate (analyte) dominates the capacitance response, charge transfer from the absorbate controls the conductance response [73]. These capacitance and/or conductance responses are therefore the two main sensing mechanisms, which are labelled "chemicapacitors" and "chemiresistors", respectively. The conventional materials from which these devices are fabricated are polymer composites and electrically-conductive particles, however the instability of the polymer/conductive particle interface can be disadvantageous for chemiresistors. Chemicapacitors show greater stability but have a slower response. However, Snow *et al.* purport that the use of SWNT alleviates these problems [71,72]. The sensors can respond to chemicals in sub-second with the change of the conductance and capacitance. Similarly, multi-walled carbon nanotubes (MWNT) have been employed as the active sensing element to detect gas by using impedance spectroscopy to measure the changes in both capacitance and resistance [74].

Changes in SWNT capacitance are mainly associated with the intrinsic dipole moment of the analyte. Changes in conductance are mainly due to the charge-transfer interactions between the analyte and the nanotubes. Such SWNT chemicapacitors/resistors can detect nerve agents,

blister agents, and explosives, which have been troublesome to detect using conventional sensing methods.

A chemical sensor constructed of an individual SWNT has also been developed for the detection NO_2 and NH_3 [75], demonstrating the possibility of nanotube molecular sensors. The sensor device was fabricated by suspending a single SWNT between metal pads acting as electrodes for resistance measurements.

3.3.2 Sensors/Biosensors by CNT-based Field-effect Transistors

Field–effect transistor (FET) sensors are another category of molecular sensor. Rapid increases in computer processing power have been driven by the miniaturisation of transistors, and due to their prevalence in electronic devices, nanoscale FET may be produced using current integrated circuit technology. Soon, the existing silicon based transistors will reach the lower limits of their physical dimensions, however, it has now been confirmed that the integration of semiconducting CNT as an alternative will allow FET to be further reduced in size, allowing their inclusion in future nanoelectronic devices [76,77]. Another advantage of CNT is their electrical conductivity, improving the transport of the electrons with less scattering. A FET consists of source, drain, and gate electrodes. In a CNT-based FET sensor, one CNT acting as a nanowire is contacted by the source and drain electrodes while the gate electrode is used to manipulate the conductivity of the nanotube (Figure 9). Since the CNT-based FET have shown promising performance over silicon-based transistors in terms of miniaturisation and sensitivity, and specific interactions with different molecules enables rapid changes to CNT conductivity, the CNT-based FET device has been quickly adapted for use in commercial sensing systems [78].

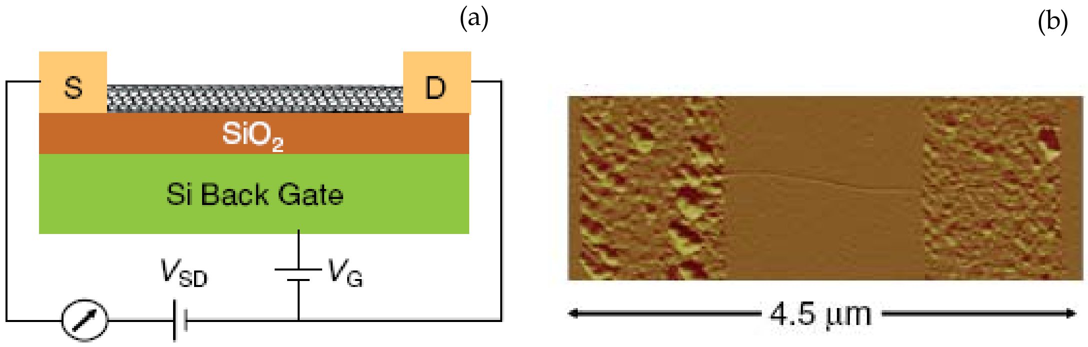

Figure 9: Field-effect transistor based sensor using a single SWNT to connect the source (S) and drain (D) electrodes. (a) Schematic structure and (b) micrograph of a fabricated device. Reproduced with permission [78].

3.3.3 Functionalisation of Carbon Nanotubes for Sensing

Sensor applications using CNTs require chemical modification of the nanotubes by functionalisation for the amplification of molecular recognition, selectivity and/or electrocatalytic properties. There are two methods for functionalising CNTs

1. Covalent attachment via the formation of covalent bonds [79]; and
2. Non-covalent attachment via electrostatic, van der Waals, or hydrophobic interactions [80].

While covalent attachment requires complex chemical reactions, the non-covalent attachment involves dispersing the CNTs in a solution of functional substances such as surfactants, or protein of polymers.

Additionally to chemical sensing, the incorporation of CNT in a sensor has the potential to address a number of long-standing issues in biosensing. This is particularly important for biological agents such as DNA, proteins, and small-molecule toxins such as bacteria, viruses, and other pathogenic organisms [81].

CNT-based transistors show great promise for use as future biomedical diagnostic and research tools, and are particularly relevant to chemical/biological Defence applications.

3.4 Smart Micro- and Nano-devices

3.4.1 Micro- and Nano-sensors

CNT-based FET sensors are an example of micro-sensors which can be further reduced to the nanoscale. Other applications include nanoparticles, nanowires, or materials with designed nanostructures. Nanowires can be of micron length, though have diameters of the order of nanometres. Nanoparticles are of diameters ranging from 1–100 nm. They are larger than molecules, similar in size to many proteins or polymer molecules, yet smaller than viruses.

Nanoparticles, nanowires, and nanostructured materials exhibit unique properties which are quite different from the bulk materials of the same molecular structure. For example, due to large surface areas, nano-sensors possess high sensitivity with several orders of magnitude better than conventional sensors and provide fast response. Another advantage of materials at the nanoscale is that the physical, optical, magnetic, and electrical properties of nanomaterials depend on their dimensions, and reveal unique characteristics that are not seen at the macroscale. This allows tailoring of optical and electrical properties by simply changing the aspect ratio, size, layer thickness, and material composition, allowing for even greater improvements in sensitivity, as well as other novel characteristics.

3.4.2 Nanostructured Surfaces

Similar to nanomaterials, nanostructured surfaces offer a wide range of functions which have not been seen in the bulk state and provide potential applications for enhancing Defence capability. In section 3.2 we described arrays of quantum dots as a nanostructured surface for high-performance IR detection. A forest of nanofibres on a substrate can generate an adhesive force due to van der Waals forces similar to that displayed by a gecko's foot [75]. Indeed, a sticky surface obtained without gluing can be achieved by the growth of nanofibres such as polyester or silicon on a substrate [82]. Recently, Qu and Dai [83] grew a CNT forest that gave an adhesive force of 30 N/cm^2. The attachment/detachment mechanisms of the sticky surface can be controlled by the surface movement. This provides, for example, the potential for the climbing of vertical surfaces.

Harnessing the movements of the human body, solar energy, wind energy can also be used in the generation of electricity for Defence personnel. The human body provides mechanical energy, heat energy, vibration energy, chemical energy, and the hydraulic energy of the

circulatory system. Additionally, wasted heat from engines, vibration from moving objects (vehicles, aircraft, and ships) can be harnessed as an energy source for nanorobotics, MEMS and NEMS (nano-electro-mechanical systems), anti-terrorism devices and personal electronics. ZnO is a typical piezoelectric semiconducting oxide, the deformation of which generates electricity. A group at *Georgia Institute of Technology* in the US grew ZnO nanowire arrays on single crystal sapphire substrate at 1000°C, fabricating a generator that converts mechanical energy into electrical energy at the nanoscale [84]. A DC current of 0.5 nA can be continuously produced by ultrasonic waves to bend the ZnO nanowires back and forth, resulting in an output wattage of ~1 pW for the nanogenerator on a scale of 2 mm^2 [85]. Wet chemistry enables the synthesis of ZnO nanowires around Kevlar fibres at 80°C [85], which is a breakthrough for the growing ZnO nanowires on fibres for practical use. It is also possible to fabricate flexible, foldable, and hence wearable "power" fabrics containing robust power sources. The fabrics can produce 20–80 mW/m^2 fabric, by brushing fibres against one another due to vibrations sustained during walking, heartbeats, ambient noise, and air/wind flow [86].

It should be noted that within MPD the Seebeck's thermoelectric effect has been demonstrated on a thin film of polymer (50 × 3 × 0.1 mm) using solar energy. With optimum conditions, the film yields a voltage of 0.74 mV and a current of 22 nA or approximately 100 mW/m^2 [87]. This value is comparable to that of the "power" fabrics developed at *Georgia Institute of Technology*, but the fabrication process employed within MPD is far simpler. These polymers should be considered for further development as solar harnessing materials.

3.5 Smart Molecular Structures

3.5.1 Molecular Electronics

Silicon microelectronics has seen a relentless pursuit of miniaturisation over the past half-century, leading to dramatic improvements in computational capacity and speed. The demand for increased information storage density has pushed silicon technology to its limits, and shifted the research focus to novel materials and device structures. Moore's law, given as a prediction in 1965 by *Intel* co-founder Gordon Moore, predicts a doubling of the number of transistors per unit area each two years [88]. However, this constant improvement could well "hit the wall" over the next decade. Molecular electronics opens the door to extend Moore's Law for the further miniaturisation of electronic, optoelectronic, and communication devices or systems. Researchers in this area have developed transistors out of carbon nanotubes, with switches connecting molecules to metal wire leads. More elegantly, scientists at *Columbia University* have developed a unique way to chemically connect carbon nanotubes through the formation of robust molecular bridges between the nanotube ends [89].

A nanoradio was recently invented [90,91], in which a single CNT acts as a combination of radio components, i.e. an antenna, a tuner, an amplifier, and a demodulator, on the nano scale. This work indicates the potential for system over device demonstration using CNT. Further work in this area is leading to the transmission of radio signals [92]. Thus, a nanoradio can be used as a nano-transmitter to relay information to a detector. Such small devices show great promise as medical implants.

Following on from CP, fullerene, and CNT, graphene has appeared as a 2-D carbon material of interest, due to its unusual optical and electronic properties. The emergence in the short term of an era of “graphene electronics” has recently been predicted [93].

3.5.2 Molecular Devices and Machines

Molecular devices and machines are inspired by biological systems. With the progress of molecular biology and the magnifying power of microscopes, natural nano-machines constituting the basic form of life have been increasingly revealed, and result in a source of inspiration for bio-mimicking. Like macroscopic devices and machines, molecular counterparts consist of multiple components. Chemists are then able to manipulate atoms and molecules to develop a bottom-up strategy for building nanoscale devices.

The combination of several molecules into a system called a “supramolecule” has allowed the synthesis of molecular devices and machines including tweezers, adaptable receptors, propellers, rotors, turnstiles, gyroscopes, gears, brakes, pedals, ratchets, switches, lifts, muscles, valves, artificial enzymes, walkers, and catalytic self-propelled micro- and nano-rods [94]. One of the main components in building molecular machine is *rotaxane*, which is a typical supramolecule consisting of a wheel (rota) and an axle (axis) as shown schematically in Figure 10. A number of excellent reviews and monographs on the topic of molecular devices and machines are available [95,96].

Analogous to the use of fuel in macroscale machines, molecular devices and machines operate via chemical reactions or configuration transformations requiring an energy source. Work in the past decade has demonstrated the ability of visible wavelength energy to be used for molecular machine power, by exploiting photochemical processes in appropriately-designed photo-sensitive molecular systems.

Molecular devices and machines underpin the development of the Defence nanotechnology capability, encompassing:

- Energy (solar energy conversion);
- Electronics and optoelectronics (logic gates and circuits);
- Advanced functional materials (electrochromic materials, drug delivery systems); and
- Sensing technology (nanosensors).

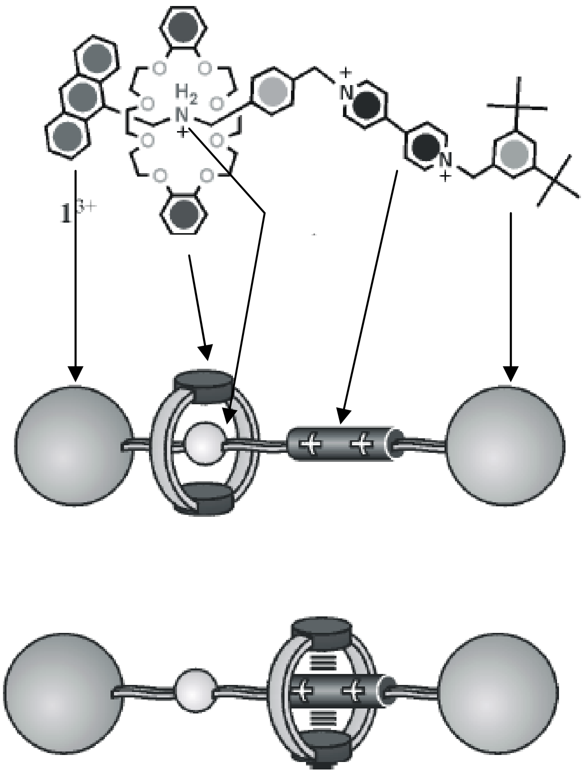

Figure 10: (a) A rotaxane supramolecule, consisting of a ring and an axis. (b) and (c) Under external stimuli, the ring is able to be shuttled between two parts of the supramolecule. Based on a schematic diagram by Ashton et al. [97].

3.6 Self–healing of Polymeric and Composite Materials

The remarkable ability to heal wounds is one of the most important inherent properties of biological systems. A bio-inspired self-healing material is one with built-in capability to partially repair damage sustained during service. Usually, material properties degrade over time due to the initiation and subsequent growth of damage such as micro cracks. The biological world demonstrates a range of mechanisms that continuously sense and repair damage. In the materials science field, researchers are now attempting to engineer this type of behaviour into man-made materials, under the banner of "self-healing" materials.

Self-healing structures are particularly important for Defence platforms consisting of polymeric materials and composites. The application of self-healing materials will aid in the prevention of degradation, thus improving platform safety.

3.6.1 Nanoparticles

Nanoparticles are an ideal candidate for self-healing materials, as they may be dispersed throughout a material and engineered to migrate to any microcracks. An example of this is the ability to render glass lenses scratch-free. In multi-layered microelectronic systems or laminates, crack repair on the microscale could be partially performed by the system itself.

3.6.2 Micro-/Nano-encapsulated Healing Agents

Self-healing materials consist of a microencapsulated healing agent and a catalyst capable of polymerising the healing agent, randomly embedded in an epoxy matrix. When the material cracks, microcapsules rupture, releasing the healing agent into the crack plane through capillary forces, which then reacts with the catalyst to repair the damage. Another approach for the healing of cracks in epoxy resins is to allow cracking to break, microcapsules containing a solvent. This solvent disperses into the matrix, finding pockets of unreacted epoxy monomers and carrying them to the crack location to restore the resin stiffness. Clearly, the effects of the initial addition and integration of healing agents into a material system on its original performance must be accounted for.

Self-healing by micro-encapsulation has been used to repair different thermosets in neat form [98,99] and in fibre-reinforced composites [100]. The chemical system that has been studied extensively for self-healing is microencapsulated dicyclopentadien, polymerised by Grubb's catalyst particles [98-100]. Self-healing efficiency is readily tested by failing components subsequent to healing processes, showing up to a 75% recovery of fracture toughness. In addition, inclusion of hollow microcapsules within an epoxy matrix can increase the toughness of the polymer by 120% [98]. Changing the capsule contents and catalyst concentration allows for recovery of up to 90% of fracture toughness.

Optimisation of the design and the efficiency for the synthesis of healing materials is still needed. Rule *et al.* [101] have studied the effect of microcapsule size on the performance of self-healing polymers. They also incorporated paraffin wax into catalyst to protect air degradation, thus enhancing the efficiency of the catalyst [102]. A similar strategy has been undertaken to improve maximum fatigue endurance limits [103]. While some researchers have tended to store healing agents in spherical microcapsules [101,102], other authors have delivered crack-stopping resin and hardener via a series of hollow glass fibres [104]. Hollow fibres filled with uncured resin and hardener are arranged in alternate layers, mimicking a blood vessel structure. A sudden impact to the material causes at least two layers to rupture leading to the formation of a cured epoxy to heal the cracks.

Verberg *et al.* [105] are investigating "artificial leucocytes" via microchannel delivery networks and polymeric microcapsules capable of sensing damage, localising at the impaired site and triggering repair. They have proposed a model in which microcapsules consist of an elastic shell, encasing a solution of nanoparticles, and have investigated via computational modelling the motion of microcapsules driven by an imposed flow on a substrate. Nanoparticles are delivered to damaged areas by the polymeric microcapsules to mend the damage. The remaining microcapsules then traverse the region and move further to sense and repair other damage. In effect, the microcapsules act as artificial leucocytes, providing a "repair and go" function.

Gupta *et al.* experimentally verified the results of this simulation [106]. They found nanoparticles dispersed in a polymer matrix migrated to a crack generated at the interface between the polymer and a SiO_2 layer, as long as the nanoparticles (of 5 nm diameter) are coated with a particular polymeric coating, in this case, poly(ethylene oxide). This ability to migrate toward and cluster around cracks is also highly dependent on the dimensions of the nanoparticles.

These results point to a simple means of fabricating systems that can self-heal, improving the durability of multilayered systems, or forming the basis for auto-responsive materials. In future, scientists will experiment with rod-shaped nanoparticles, as well as further exploring the level of migration seen with nanoparticles with varying coatings and sizes.

3.7 Recommendations

In the short term (2–5 years), DSTO should maintain its focus in CNT fabrication and smart materials and multifunctional materials based on CNTs, functionalised CNTs, CP and CNT/CP composites. In the medium-to-long term (5–15 years), research should be focused on the fabrication of biological/chemical sensors and EM-responsive sensors, molecular electronics, and self-healing structures. Collaboration with HPPD expertise in organic synthesis and other nanostructures should continue, and consideration given to expanding MPD effort in this area. MPD should consider linking through TTCP, existing *University of Wollongong* linkages to international research conducted in the US, Europe, China, and Korea on unclassified topics of Defence interest, for which research in CNTs and CPs would be an appropriate starting point.

4. Electromagnetic Signature Management

4.1 Meta-materials

Much work in electromagnetic (EM) signature management has been in the area of meta-materials; those exhibiting non-standard EM properties. Normally, materials have relative permittivity and permeability values greater than unity (relative to free space), which gives rise to the effects of conventional refraction and diffraction. Meta-materials can show effective negative permittivity and/or permeability values over a specific frequency band, leading to unusual and interesting effects, most notably in the field of lenses, EM absorption and "cloaking". These EM effects are frequently obtained through macroscopic arrangement of materials and structures.

A review of meta-materials and their possible uses by Ozbay *et al.* [107] gives an overview of recent advances in both theoretical and practical research aspects of meta-materials, and research activity has progressed to the stage where *Elsevier* has published a new journal entitled "Metamaterials" to collect related work in this field.

Of most interest to Defence is the ability of meta-materials to "cloak" an object by diffracting EM waves around an object, be they at radar, visible, or IR wavelengths. This approach differs to normal absorption mechanisms in that the waves travel *around* the object without actually interacting with it, and then recombine at the other side of it, leaving little trace of the object being there. This concept was strictly theoretical until a working prototype was recently demonstrated at microwave frequencies [108]. The device was a 2D ring of concentric circles containing split-ring resonators as the meta-material, and showed a cloaking effect at a single frequency. Since then, much modelling and experimental work has followed with a goal to produce a working prototype at optical frequencies, and extend the frequency range over which the material "cloaks" an object.

Theoretical modelling has also shown that it is possible to produce a material which is effectively "invisible" in the visible band [109]. Currently, the prediction models are only valid for a single wavelength, and the effect has been demonstrated at 632.8 nm, corresponding to the colour red. This technique could potentially be used to defeat a particular-wavelength laser rangefinder. It may also be possible to extend the technique to provide invisibility over a series of wavelengths or a wavelength band.

4.2 Flexible Display Panels

It has recently been reported that the British Army have used "lights and mirrors" (or more correctly "screens and projectors") to render a tank invisible to soldiers in the field [110,111]. This approach can be effective, but is cumbersome in the extreme. Of greater interest is the ability to use video cameras and flexible Organic LED or electronic ink display panels adhered to the sides of platforms to display an image of the scenery directly behind the platform. This would give the effect of invisibility at a distance, and would be reasonably easy to implement, once the screens were in place. Current technology only allows for black and white or limited grey scale capability with these flexible displays, however work is continuing in the private sector in the areas of mobile phone displays and roll-down television screens. However, a

working prototype may be demonstrated within 10 years. Further advances to project an image in the near-IR region may also be possible.

In the shorter term, electrochromic materials are currently used to darken car sun roofs, or windows on buildings [112]. Instead of using a blind, a current is passed through the glass coating which darkens the window. Varying the current allows control of the amount of shading. This has great application for darkening or brightening the sides of a platform to better blend in with the surroundings. The film can be applied to an entire structure, and may be modified by the turn of a dial or automatically using a light intensity sensor.

A number of related technologies are competing in the smart-window area:

- Thermotropics;
- Photochromatics;
- Liquid crystals;
- Suspended particle displays;
- Electrochromics; and
- Reflective hydrides.

Thermotropics and photochromic devices can be used to darken windows, but they cannot be manually controlled. The other technologies can be used to adjust the brightness and transparency of the coating with the turn of a dial.

4.3 Active Radar Absorbers

The reduction of radar cross section (RCS) on military platforms is important in reducing a vehicle's detectability. By presenting a lower RCS to a radar source or guided missile, the probability of detection by the searcher or being struck by the missile is reduced. Radar Absorbing Materials (RAM) are used frequently on high-value platforms to lower the RCS, however the physical properties of the RAM such as thickness and weight are determined by the frequency range over which the material is designed to operate. This requires knowledge of the frequency band employed by the threat, which varies with sensor, or can consist of multiple frequency bands. Passive RAM needs to provide maximum performance at the most likely frequencies whilst still providing a lower level of protection over a wider frequency band. This makes material selection and production difficult, and increases the weight, thickness and complexity of the final product.

In contrast, an active system could be used to provide maximum performance at the exact frequency that an incoming radar source is using. By using a radar detector it is possible to scan the area surrounding the platform for incoming waves and adjust the performance of an active material to reduce the RCS at that frequency. A lightweight, multi-layer material could be made to cover a wide frequency band, providing high performance levels for both long range surveillance radars through to missile seeker and aircraft radar bands.

The use of Frequency Selective Surfaces (FSS) controlled by "PiN" diodes, and meta-materials with negative values of permittivity and/or permeability are currently being studied as a way to alter the reflectivity of a multilayered material. Real devices are being produced in

laboratories that confirm theoretical predictions. Materials that show very little absorption in their passive state can be "switched on" by the application of a 0.1 mA current and reduce the RCS of the material by more than 30 dB (see Figure 11) [113]. Materials that show a high performance at one frequency can be altered using an applied field to provide the same high level of absorption at a different frequency [114].

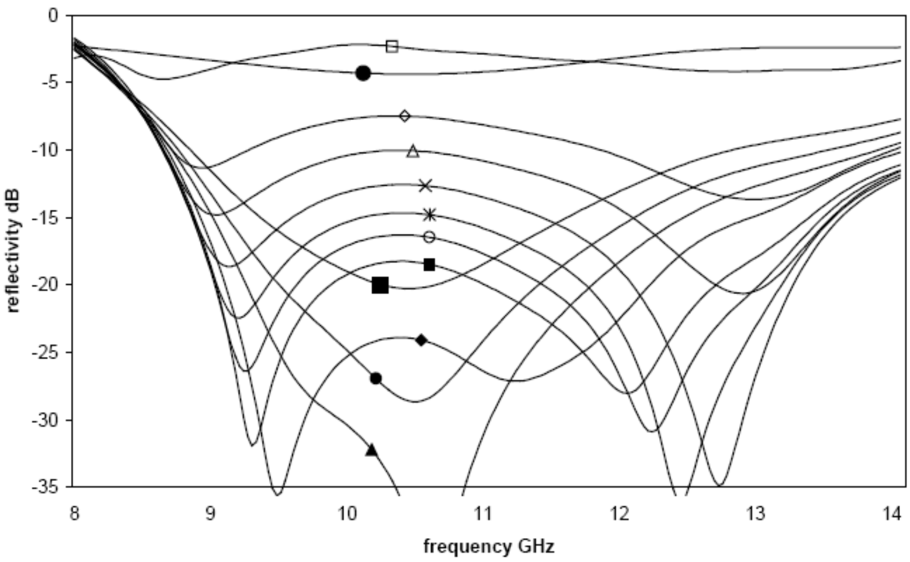

Figure 11: Measured reflectivity as a function of applied current. □ = 0.0 mA, ◇ = 0.025 mA, △ = 0.05 mA, 3 = 0.06 mA, ✳ = 0.07 mA, ○ = 0.075 mA, ■ = 0.085 mA, ▲ = 0.1 mA, ● = 0.11 mA, ■ = 0.13 mA, ● = 1.0 mA. Reproduced with permission [113].

4.4 Recommendations

MPD should instigate research into the use of FSS or meta-materials for the reduction of radar reflection over a range of frequencies, for which existing microwave measurement facilities can be used, and material components may be manufactured using in-place printed circuit board technology.

5. Sensors and Sensor Systems

5.1 Sensors as Disruptive Technologies

Sensing and quantification of various physical parameters has improved incrementally over many decades and centuries, and pervades a broad spectrum of physical, chemical and biological properties, as well as utilising and measuring radiation across the electromagnetic spectrum. In the modern military context, timely analysis of variables provides for punctual decision-making on the future course of operations. This in turn will improve efficiency and increase the likelihood of achieving outcomes. The advancement in fundamental sensing technology has been somewhat outpaced by the more rapid advancements in the conversion of sensed information into electronic signals for presentation to either an end-user or an information processing system.

The majority of sensing is aimed at either a single parameter or, if inaccessible, the most closely-related property. Recent work has increasingly focused on accurate sensing with miniaturised components in order to sense many parameters from a single location. Substantial work has been performed at DSTO on the miniaturisation of sensors and sensor systems in order to incorporate them on weight-sensitive structures such as aircraft [115-120]. Sensing at high resolution tends to occur over small dimensions, whereas at the battlefield level, the focus of the military commander is on large scale dimensions and movements, at relatively lower resolution.

5.2 Identification of Sensing Parameters

In a Defence operational context there are a multiplicity of variables that may be measured and monitored and with the continuous improvement in computing power, there is significant potential to acquire large amounts of data [121,122]. However, it is the definition and selection of the desired parameters that will yield optimal sensing and measurement regimes.

Variables of interest from a Defence operational perspective are clearly those that affect the outcome of an engagement, through information gathering on large-scale factors such as enemy location, movements and equipment, and smaller-scale measurements on the state of capability of one's platforms and hardware. While it is highly beneficial to acquire and analyse some data in real-time [123,124], other information may be acquired and processed at a later stage with equal relevance. In the context of Australian Defence operations, a number of systems and their associated properties that are of interest in the development of sensor technology are outlined here.

5.3 Current Sensor Capabilities and Challenges

5.3.1 Precursors to Adverse Effects

In many cases time is the key variable to the appearance of a significant opportunity or threat, and it is thus beneficial to measure properties that indicate the beginning of adverse processes, so that preventative rather than corrective action may be taken. This includes battlefield-level complex sensing of enemy positions and movements [125], and is also particularly relevant to the physical and environmental processes that occur in the degradation of materials on a gradual scale. While these precursors may not be of significant interest as isolated properties, they provide key data into consequential processes [126], particularly where the parameter of interest is difficult to measure, such as is the case with hidden corrosion in multi-layered structures.

5.3.2 Materials and Structural Health

Materials form the basis of all technological components as structural and stress-bearing members and carriers of energy waves and communications signals. Fundamental properties including strength, elastic and bulk modulii, density, electrical resistivity and magnetic permeability of standard and more exotic, anisotropic materials are generally well characterised and understood, particularly where they perform crucial structural functions. Testing and inspection of advanced materials occurs during both manufacture as well as the joining stages in order to qualify them for service [127,128]. However, while material properties may be well-characterised prior to employment, structures are increasingly designed closer to their limits to remove performance restrictions and cut unnecessary costs [129], and the verification of structural materials operating according to design specifications is crucial.

The onset of degradation of a bulk material is detectable by multiple routes. Physical degradation including cracking, discontinuities and delaminations can be sensed non-destructively using energy across the electromagnetic spectrum, with techniques such as [130]:

- X-radiography;
- Penetrant testing;
- Ultrasonics and acoustic emission;
- Microwave frequencies;
- Electromagnetic techniques;
- Thermography and its variants [131]; and
- Optical and deformation field techniques such as shearography [132,133] and fibre-optic sensing [134,135] (Figure 12).

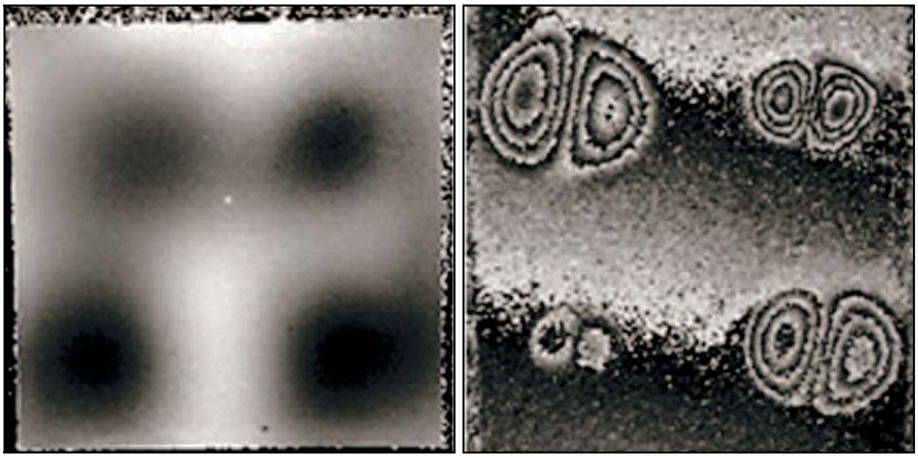

Figure 12: Thermographic (left) and shearographic (right) representations of simulated circular defects in aluminium-skinned structure. Reproduced with permission [131].

Nondestructive inspections are generally specific interrogations at particular material locations identified as being most susceptible to degradation, as a "weakest link" indicator. On known materials and structures, nondestructive testing and evaluation research is advanced to the point that the reliability of specific inspections is well understood, and major new work relates to modelling to allow for optimisation of inspection schedules and the reduction of downtime and maintenance costs [136].

Corrosion of structural metallic components is a major problem, exacerbated by the location of platforms in harsh environments, such as near coastlines. The techniques above can detect corrosion as a loss of material thickness (or increase due to the presence of corrosion product). This detection may not occur before a significant amount of a component has been damaged, and hence the analysis of properties such as those listed in §5.3.5 may provide a more sensitive measure of the onset of corrosion.

A substantial body of work has also been reported on permanently-mounted SHM systems, in which networks of many sensors are permanently located at material "hot-spots" and then regularly interrogated for variations in material properties [137-140]. An increasing focus on wireless systems is enabling more convenient applications with lower weight and wiring requirements [141,142].

5.3.3 Human Operators and Combatants

Characterisation of the factors affecting human operators is a complex field, and the variables of interest are typically multifaceted in comparison to material properties. As parameters related to human performance are vital in a Defence setting, measurements can relate to subjective parameters that are difficult to isolate and repeat-measure.

Defence Force personnel face a broad spectrum of risks from chemical, biological, radiological and potentially nuclear hazards. There is a wide variety of natural and synthetic chemicals, toxins originating from plants or animals and other biological materials, including disease micro-organisms and bacterial eco-toxins, that have either been used as warfare agents or are

considered to have the potential to be used as such [143]. Research related to these agents has also markedly increased in recent years [144].

The detectability and ease of identification of many of these agents can be made in real time using either portable laboratories or handheld field systems [145,146]. This allows for a potentially rapid response to ensure personnel safety in the face of chemical agent exposure. Medical sensing and detection for the purposes of diagnosis subsequent to adverse exposures occurs across a broad range of techniques, although incapacitated troops would generally be removed to a more amenable location for regular medical testing. In civilian medicine, remote wireless sensing is being investigated for the monitoring of heart patient health and other studies [147]. Work on wearable SAMI (soldier acceptable, minimally invasive) sensors, including blood sampling by laser poration (the creation of micro-pores in the skin), has been underway for over a decade [148].

Human fatigue due to physical exertion is a key property of interest to a military commander. While complex by nature, there are a number of lower-level measurements that may be acquired and collectively analysed in order to quantify fatigue, including:

- Mean skin temperature;
- Core temperature;
- Heart rate;
- Degree of hydration;
- Weight loss;
- Oxygen consumption; and
- Metabolic stress [149].

It has also been suggested that the measurement of cortisol hormone levels has a direct correlation to the level of “stress” being experienced by a soldier, as well as being a biomarker for a number of medical conditions, and a patent exists to prototype this technology [150].

Biomedical measurements of the kind discussed here may be made in the laboratory and the field for benchmarking studies, using either standard or advanced test and measurement equipment [151,152] with more advanced biosensors including thermal conductivity meters to measure skin blood flow [153], or for the determination of troop “vigilance” [154]. Figure 13 shows the quantification of endogenous thermal stress experienced by troops on exercise, via the measurement of oxygen consumption using an ergospirometer. Peaks in the curve occur during manoeuvres requiring greater physical exertion. Real-time analysis of substantial numbers of Defence personnel, utilising “wear-and-forget” sensors for health monitoring on routine operations is a significantly greater challenge, requiring further advancement [148].

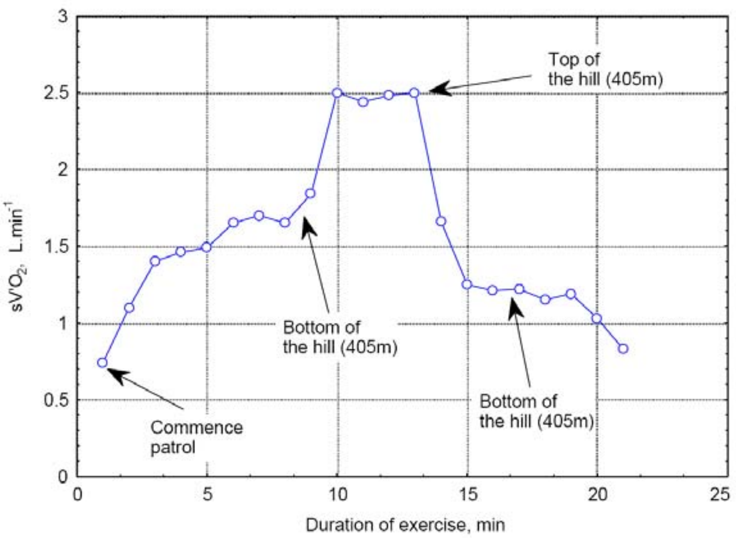

Figure 13: Determination of endogenous thermal stress by measurement of oxygen consumption in soldiers on exercise. Reproduced from [152].

5.3.4 Electromagnetic Radiation

Functionality of equipment and hardware impacts directly on the degree of operational success, and can be subject to interference from external signals and radiation. In the sphere of electronic warfare, radiation over a broad band of the spectrum ranging mostly from radio to infrared is measured, depending whether the focus is on electronic support, attack, or protection [155,156], or in the gathering of signal intelligence to create a picture of the electronic order-of-battle [157]. Significant research is performed on the protection of sensor networks from attack [158], however the bulk of research related to this area is expected to be reported in the classified literature.

A more advanced problem is the measurement of exposure of personnel to directed energy from non-ionising sources. Working in a radiation intense environment that causes over-exposure is known to cause damage to human tissue [159,160], although symptoms may not become apparent in the short term.

Radiation in the Terahertz (10^{12} Hz) band [161] has shown promise as a diagnostic and inspection tool, with the potential for biological and general detection and sensing [162,163]. It has also been studied for the detection of medical tissue abnormalities [164], and cancer-related research [165].

5.3.5 The General Battlefield Environment

The environment in which operations are conducted presents a number of variables of interest. These may be fundamental physical parameters, or the result of complex analyses as outlined below.

Environmental factors, encapsulating the naturally-occurring external circumstances within which personnel and equipment operate, contain physical components that affect operational performance, and include:

- Temperature
- Humidity
- Corrosivity
- Salinity
- Precipitation
- Visibility
- Smoke presence
- Chemical/biological agent presence
- Wind
- Sea state
- Terrain, and
- Air pressure.

These parameters could all be sensed readily in a large-scale military operational environment, and they also affect the performance of sensors measuring changes in the environment, such as surveillance sensors [166].

Sensing parameters of much greater complexity include those related to the automated detection and recognition of objects in images using machine intelligence in software and hardware systems [167,168]. The focus of sensing systems of this kind includes:

- Detection of the presence of humans [169-172];
- Detection of inanimate obstacles that impede physical motion of autonomous military platforms and equipment [173-176]; and
- Hostile objects that will impede or destroy the success of a mission, including explosives [174,177-179].

Work is underway on discriminatory sensing that aims to distinguish between the presence of military and civilian personnel using an array of metal-detecting sensors [180].

5.4 Challenges for Sensing

Few physical properties relating to Defence operations and military platforms cannot be directly measured. Challenges are typically reported as arising in the measurement of high-level and intrinsically complex variables such as mental stress levels and other human factors such as "sense of purpose" and troop "morale" [181]. While the effects of influences on these parameters give reliable qualitative data, the measurement of repeatable quantitative data is difficult [182]. Specific factors have been derived according to a wide analysis of metrics, such as the Pressure Management Indicator [183].

Application-specific scenarios exist in which insufficient time or other resources are available for a measurement of sufficient accuracy to be taken under regular procedures. These

problems are generally treated by application-specific minor improvements or compromises on existing systems to match the specific need.

Increased accuracy and resolution is a constant aim in sensor research [184], and these are generally associated with incremental improvements. Other approaches can be taken to negate the ubiquitous challenge of resolution versus coverage, for example an extended sensing range is achieved by mounting sensors on unmanned aerial systems with greater penetration into a surveillance region.

Sensors are increasingly able to provide real-time information to the battlefield commander, and significant effort is applied to the processing and analysis of sensor data [185,186]. A challenge for sensor systems is to provide relevant decision-making data at a high level to positively influence the operator or commander's situation awareness [187]. Information overload can easily occur and the net productivity gain resultant from data acquisition from C4I-type sensor systems in military operations is the subject of discussion [188]. The formation and exploitation of sensor networks that are autonomous is considered to yield a significant operational advantage [189,190], coupled with successful two-way information flow between the higher and lower operational levels on the battlefield [191]. This requires significant work into the operation, integration and updating of live sensing and communication data layers [192].

A schematic example of typical high-level sensor tasks involved in an operation simulation is shown in Figure 14.

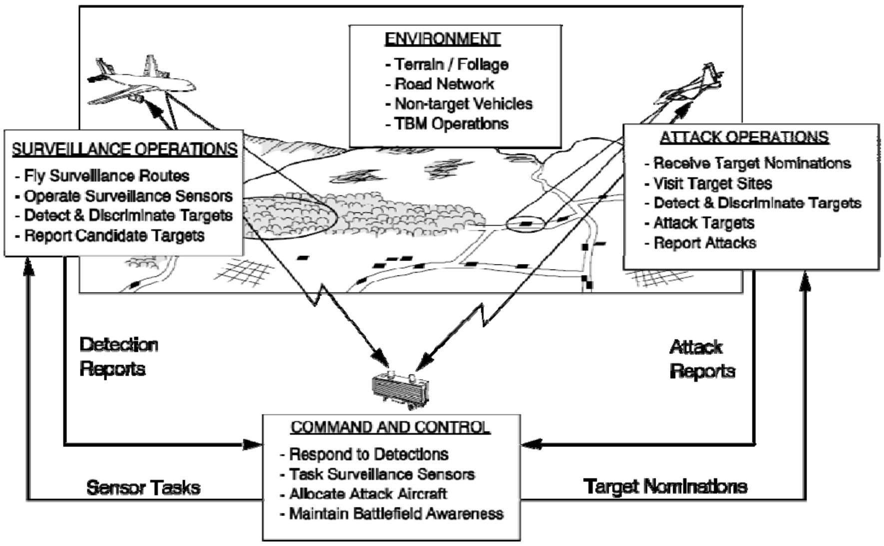

Figure 14: A schematic description of high-level sensor tasks related to the simulation of a surveillance and attack operation. © 1998 IEEE. Reproduced with permission [188].

At this level, the performance of individual sensors is often treated as given, and the focus is placed on the distribution of sensors in a system and sensor and data fusion [193,194].

5.5 Recommendations

Resource constraints prevent detailed expertise in a wide range of sensing technology from being maintained at DSTO. However, deep understanding in areas of short-to-medium relevance to platform technology is required. Sensor data are being acquired in vastly increasing amounts, producing a requirement for expertise in intelligent processing and decision-making processes by which the data will be handled. This is likely an area where Systems Divisions have significant expertise to offer MPD and DSTO, and it is noted that a DMTC/NDE project is already investigating the area of automated defect classification. MPD should be prepared to invest early in the development of expertise that might be required in medium-to-long term Defence acquisitions and projects. Developing an understanding of both the materials and structures that DSTO research will likely be focused on in the future will provide better incubation space for the fostering of clever ideas and implementation when the opportunities arise.

The expansion and increased scrutiny of Australia's maritime borders also underlines the requirement for a wide range of sensors, for both airborne and maritime surveillance. Autonomous sensors deployed in littoral shipping channels will be increasingly required to alert UAVs and manned platforms to the need for closer surveillance. In the future Australia will also need to make increased use of satellite surveillance, so developments in satellite remote sensing should be monitored.

6. Data Management & Processing

6.1 Data Management

Data acquisition, management, and manipulation are vital in making the "right" decision. The *US Joint Vision* for 2020 [195] states:

> *"… [we] must be able to take advantage of superior information converted to superior knowledge to achieve "decision superiority"—better decisions arrived at and implemented faster."*

There are several approaches that can be used to resolve a problem or question and reach a decision or solution. They can be based around a series of rules, models or cases/scenarios [196]. The data obtained from all levels and sources need to be able to be integrated so it can be effectively used. If the data are scattered, duplication occurs, resulting in poor decisions, inefficiencies and errors [197].

6.2 Data Requirements

The first considerations prior to the acquisition of data is how those data will be used, by whom, and when [198]. That is:

- Will the data be used locally (i.e. by the operator to determine the health of the system and whether failure of part "X" is imminent, affecting the ability to carry out the mission)?
- Will the data be used by a commander to make strategic decisions?
- Will the data be used by a maintainer to perform a maintenance/repair action?

The decision-makers have differing perceptions, motivations, and attitudes, depending on their position as stakeholders, subject matter experts, or analysts [199]. French & Geldermann [199] have represented the decision making process as shown in Figure 15.

Once these questions have been addressed, further investigation relates to quality of the data and where those data will be processed.

Data quality may affect the ability of the system to make a decision. Is the degree of accuracy required as an order of magnitude or to the third decimal place? What impact will noisy data have on the decision? How will the system approach the problem of missing data [200]?

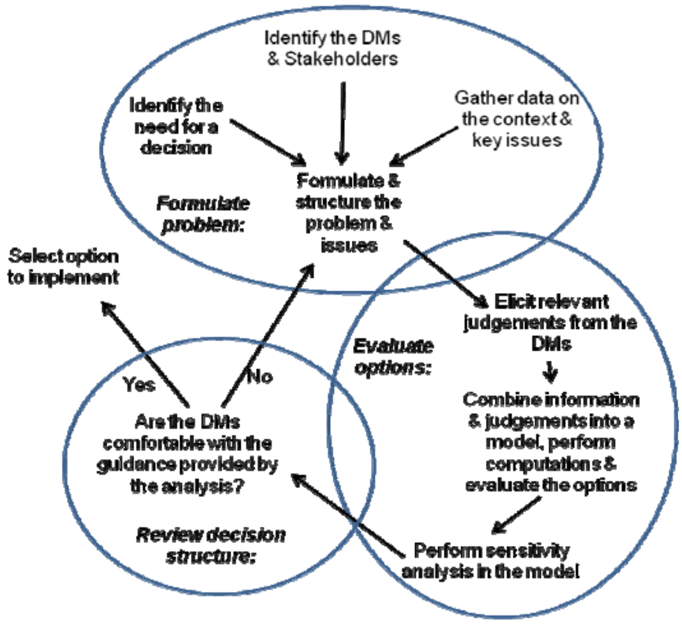

Figure 15: The decision making process. DMs = Decision Makers [199].

Rough Set Theory is a mathematical approach to dealing with vagueness and, as a result, imperfect knowledge or data [201]. It can be applied in the following situations:

- Machine learning and pattern recognition;
- Knowledge Acquisition;
- Decision Analysis;
- Data mining and knowledge discovery from databases;
- Expert Systems; and
- Conflict Analysis.

Ranilla and Rodriguez [202] discuss a mathematical approach to developing rules when the data may be incomplete or imprecise. This discussion is beyond the scope of the current review.

If the data and subsequent outputs affect the ability to carry out the required mission effectively or safely, the data will need to be processed locally to allow for real-time feedback. If the data impact on strategic decisions, they could be processed centrally, but this depends on the available bandwidth. Some data processing may need to occur locally, with a single output transmitted. If the data are being used to perform a maintenance/repair action then they can be processed after the fact, however this will be dependent on storage capacity of the on-board system, and the need for data analysis to determine why the system had failed. The amount of data collected and stored will also depend on how the data will be used and managed. That is, will they be used to provide a global view of the mission or a very fine analysis?

The way in which data are distributed is determined by who needs to use the output. Is immediately transmission required? Can data be stored for subsequent downloading at a convenient time?

A battlefield scenario might consist of immobile sensors and gateways for distributing information but with mobile soldiers within the area of interest who need the information to effectively carry out their mission. As a result an *ad hoc* network can be established in which the soldier only receives reports of relevance to themselves, rather than all the reports. This provides benefits such as a reduction in network traffic, improved data transmission rates, and lowered risk of information overload. There are two possible options for such a network [203]:

- *Centralised*. Reports are sent to a command post and then distributed to the soldiers based on their location; and
- *Distributed*. The soldiers subscribe to a gateway and only reports relevant to that gateway are transmitted and received by the soldier.

The distributed method offers efficiencies over the centralised method, but further work is required to implement these methods [203].

A "common" language or framework needs to be established for the data collection and the output generated. If it changes over time, how does the system cope? This may be the result of baseline drift in a sensor, or it may be more complex due to a shifting frame of reference in which an entity that was previously considered a foe is now considered a friend.

Depending on the situation, it will likely be necessary to draw data from multiple sources, resulting in a "common" language/framework [199,204].

Whatever the output from the data analysis, it is imperative that it be provided in a useful form to justify its preparation.

The decision making process may generate: [205]

- A series of options to choose from;
- A preferred option; and
- A specific action.

6.3 Data Manipulation / Data Mining

The manipulation of data or mining of a database can be used to establish correlations or other non-random patterns that may have otherwise not been detected [206]. Data mining is useful where huge volumes of data are being generated and stored. However, the patterns that are derived need to be in an understandable form to the end user rather than the output of a "black box" [207].

Data mining can be defined as:

> *"The non trivial extraction of implicit, previously unknown, and potentially useful information from data" [208].*

Typical tasks data mining can be used for are: classification and prediction; clustering; association analysis; time series analysis; and deviation analysis [209]. Data mining should be the first step in determining if any trends exist [208]. There are potential pitfalls to data mining [206], including: bogus correlations; evidence to support any preconceptions; story-telling; and using too many variables.

Subject-matter experts (SME) are still required to determine if the discovery or trend is considered a problem and needs to be acted upon [208]. Data mining can produce a large number of rules [210], the validity of which an SME may determine based on their experience.

French & Geldermann [199] have also assessed the decision-making process based on the degree of structure contained within the problem and the level of support required to reach a decision. They have summarised it diagrammatically as shown in Figure 16.

Levels of Decision Support

Level 3: Evaluation & ranking of alternative strategies in the face of uncertainty by balancing their respective benefits & disadvantages

Level 2: Simulation & analysis of the consequences of potential strategies; determination of their feasibility & qualification of their benefits & disadvantages.

Level 1: Analysis & forecasting of the current & future environment

Level 0: Acquisition, checking & presentation of data, directly or with minimal analysis, to DMS

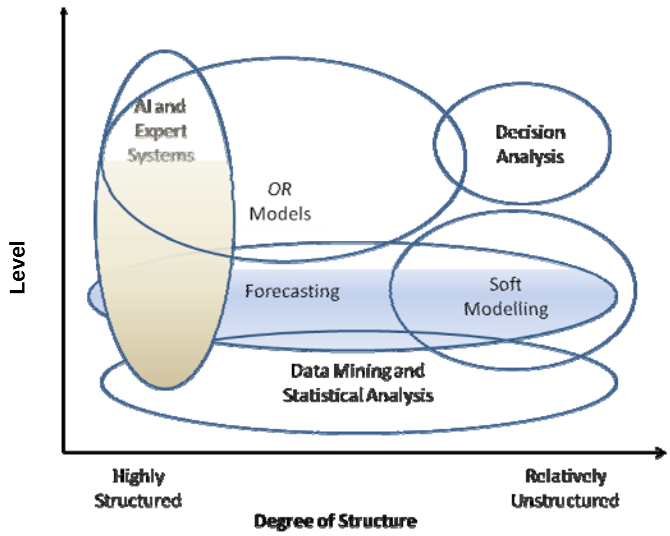

Figure 16: The data-analysis method should be chosen based on the level of structure within the problem and the level of decision support that can be provided [199].

There are numerous methods of manipulating and analysing acquired data, including:

- Artificial Intelligence/Neural Networks;
- Decision Trees;
- Genetic Algorithms;
- Fuzzy Logic;
- Data Visualisation; and
- Autonomous Intelligent Agents.

Each of these systems will be described briefly.

6.3.1 Artificial Intelligence/Neural Networks

Neural networks are universal approximators [211]. They are used mostly for complex applications where it is not possible to derive a mathematical model [212]. They provide no explanation as to how a particular decision or conclusion was reached [211]. Neural networks mimic the ability of the human brain to find patterns and relationships. They are effective at organising data and predicting results especially for non-linear systems [213].

Neural networks have the following properties [206]:

- They take time to train, requiring a large amount of resources and training data;
- They are not explicit and are considered “black boxes”; and
- They cannot arrive at an answer that a human wouldn’t. They need to be programmed with problems and solutions.

Logistic Model Trees (LMT) can be used to extract a symbolic representation of the neural network decision processes. LMT are an adaptation of Decision Trees which will be described below. LMT replace the terminal nodes in decision trees with logistic regression functions [211]. However the clear lack of explanation as to how a decision was reached limits the acceptance and general use of neural networks [207,211].

6.3.2 Decision Trees

Decision trees are a graphical representation of the decision process [211].

Decision trees have the following properties [206]:

- If the training data set is noisy then a valid tree may not be found;
- The data must be interval (discrete) or categorical. If not, then recoding will be required;
- The accuracy of the output is dependent on the number of classes or categories in use;
- They cannot be used to provide estimations; and
- They are not applicable to all types of data mining.

6.3.3 Genetic Algorithms

Genetic algorithms have had limited applications [206]:

- They have not been applied to large scale problems; and
- They require significant computational effort.

6.3.4 Fuzzy Logic

Fuzzy logic has the following limitations [206]:

- There is a lack of knowledge or misinformation about fuzzy logic and the solutions derived;
- It may not be applicable to all situations; and
- Conventional methods can work equally well.

6.3.5 Data Visualisation

Data visualisation has the following notable property [206]:

- As the volume of data increases it becomes increasingly difficult to discern patterns.

6.3.6 Autonomous Intelligent Agents

Intelligent agents are programmed with the mental attributes of Beliefs—Desires—Intentions. Imbibed with these attributes, they have the ability to handle vague or imprecise data sets [214].

Multi-agent systems have the ability to solve complex problems that a single agent would be unable to solve [215]. They rely on their properties of collaboration and autonomy.

Multi-autonomous intelligent agents can be used to take data from separate legacy systems and combine them to arrive at a decision. Using a rule-based expert system they can be used to interpret or classify data. Using model-based reasoning, they can also be used to validate data. These systems have the advantage of freeing engineers from the burden of manual data manipulation [216].

Autonomous intelligent agents exhibit four key characteristics [216,217]:

1. Autonomy;
2. Social ability;
3. Reactivity; and
4. Pro-activeness.

Standards have been developed for autonomous intelligent agents that allow interoperability between systems from different companies (e.g. Foundation for Intelligent Physical Agents). The Agent Enhanced Decision Guide Environment is an open-architecture software environment for agents (JAWS). However some of the associated standards are still being developed and are evolving.

Adding or removing agents from a multi-agent system can be trivial and can occur while other agents are running.
Intelligent agents have been used to analyse data and generate recommendations [195]. An example most people would be familiar with is adaptive computer interfaces such as the Microsoft Office Assistant [218]. The system learns from the actions of the user and the activity being performed and the intelligent agent can offer suggestions and recommendations while tasks are being performed.

Intelligent agents can be used to control engineering tasks. Their intelligence ranges from rudimentary sensor monitoring and data reporting through to decision making and autonomous behaviour [219]. The reasoning engines within intelligent agents can be from the data mining of historical databases, decision tress or rule-based engines [219].

Odubiyi, Rouff and Chi [220] make use of a pyramid of knowledge to describe the movement from a sensor output to an action or outcome as shown in Figure 17.

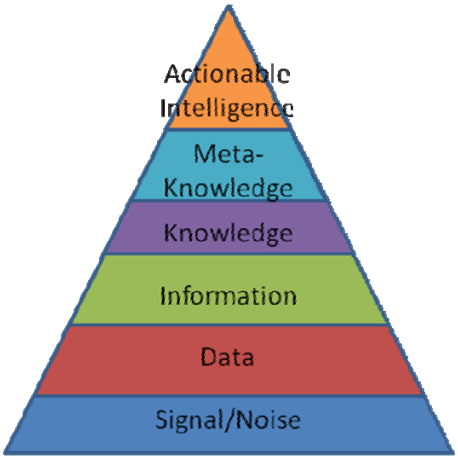

Figure 17: The Pyramid of Knowledge showing the transition from signal/sensor output at the base, to actions at the apex. © 2005 IEEE. Reproduced with permission [220].

A hierarchy exists as the signal is transformed into actions. The signal received from a sensor is worthless until it is analysed. The data generated contain information that may be useful. This information can be transformed into useful knowledge. The knowledge will contain rules about the information, e.g. *A* AND *B* = *C*, while *A* AND NOT *B* = *D*. Meta-knowledge holds rules about the knowledge. Finally when the meta-knowledge and knowledge are used in a beneficial way, they are transformed into an intelligent action.

6.4 Data and Output Validation

Problems arise in the analysis of limited data sets. Data sets must be split into two for training and testing/validation. Techniques for machine learning from small data sets include [221]:

- Mega-trend diffusion technique;
- Back propagation neural network;
- Support vector machine; and
- Decision trees.

If data sets contain less than ten items the mega-trend diffusion technique and back propagation neural networks are preferable to the support vector machine and decision tress, however further research is required on these methods.

6.5 Recommendations

The key recommendations from the review of data management and processing are to invest in the study of methods related to the control, handling, and analysis of data flow from sensors and smart materials, and to engage in existing DSTO expertise in this area that will likely be of benefit.

7. Linkages

A list of current external research linkages to MPD and relevant research areas is included in this Section.

- *Advanced NanoTechnologies*. New nanoinorganic oxides for coatings;
- *Aerosonde*. UAV engineering improvements and flight trials contract;
- *ANSTO*. Surface processing technologies;
- *ARC*. Networks on advanced materials and nanotechnology. CoE in electromaterials science;
- *ASC*;
- *Austal*. Aluminium hull management;
- *Austrian Academy of Sciences*. Ultrafine and nanostructured maritime composites and materials;
- *Boeing*;
- *BAE Systems*. Health monitoring systems and sensors;
- *CAST CRC*. Corrosion protection of magnesium;
- *CIEAM*. Corrosion sensor evaluation, prognostic health management, evaluation of acousto-ultrasonic systems;
- *CPE Systems*. In-situ eddy-current sensor arrays;
- *CRC-ACS*. Bragg fibre gratings for strain sensing, acousto-ultrasonics, NDE;
- *CSIRO*. Sensor technology and systems architecture for corrosion sensing. Potential interest severe plastic deformation and chemical/biological sensing;
- *DMTC*. Corrosion prognostic health management;
- *Erich Schmid Institute of Materials (Austria)*. Ultrafine and nanostructured maritime composites and materials;
- *Flinders University*. Sol-gel coatings for corrosion protection;
- *MiniFab*. Sensor microfabrication and novel packaging. Network clustering;
- *Monash University*. Ionic liquids, sol-gel coatings, and optical-fibre coatings for corrosion protection. Acousto-ultrasonic modelling;
- *NanoSperse (USA)*. Dispersants for nanomaterials;
- *NanoVic*. Carbon nanotube technology;
- *Rosebank Engineering*. Field-deployable supersonic particle deposition;
- *Swinburne University of Technology*. Microfabrication, MEMs, Bragg optical fibre sensing. Surface processing technologies;
- *University of Adelaide*. CoE in Photonics. Optical fibre sensor technology for corrosion and fuel degradation monitoring;
- *University of Melbourne*. Nanocoatings, polyoxometallate catalysts, severe plastic deformation and surface processing technologies;
- *University of Queensland*. Paint degradation modelling, morphology;
- *University of Technology Sydney*. Nanostructured coatings to reduce degradation of metallic components; and
- *University of Wollongong*. Smart materials and structures for sensing and self-healing. Conducting polymers for smart micro-actuation.

8. Recommendations

The previous sections (2.10, 3.7, 4.4, 5.5, and 6.5) have identified key recommendations regarding areas of research in smart materials and sensing technology where MPD should focus LRR. These are provided as a guide for the MPD Executive to identify areas in which the limited LRR resource might be applied, and should be assessed within the strategic context that the ADF, DSTO, and MPD operate. Parameters for characterising recommendations include: technical readiness and timeframe; the place in the innovation cycle; and models for engagement.

In order for MPD to be able to identify and exploit potentially disruptive technologies in smart materials and sensors, it is necessary to have a critical mass of researchers performing basic research in key areas of smart materials and sensors science and technology. The smart materials areas selected should have a high potential for evolutionary developments of relevance to the ADF, and should include fundamental research in each of the broad categories of metallic alloys, polymers/composites and ceramics. The aim is to ensure broad coverage of the literature and linkages with other Australian and overseas researchers so that awareness is maintained of new developments in these fields. Staff who are actively researching such materials will likely have a deeper appreciation of the significance of scientific and technical developments in related materials in their domain, and an ability to rapidly initiate or respond to revolutionary developments and their exploitation. A similar argument applies to the choice of sensors researched.

With the approval of MPD Executive, if a particular area is then identified as showing promise for exploitation, a team can then be drawn together to further develop concepts and to initiate the required linkages with, for example, academia or industry. Such teams would be given well defined terms of reference, a budget, and freedom to further explore the topic within an agreed timeframe (perhaps 6–12 months, depending on the complexity of the topic). Subject to progress reviews, the project would then transition to a CTD, the DMTC, or similar, with the goal being to develop a viable product for ADF application within 3–5 years. As the concept transitions to prototype and product, the research component would be scaled back markedly, with only a minor component for product development support. The majority of researchers on the team would revert to their evolutionary research in their chosen domain. Should, after the agreed period, a project appear unlikely to yield a viable outcome (as might be expected for the majority of projects which meet the inherent high risk criterion of a disruptive technology) then the team should be disbanded and revert to their substantive research. Lessons learned should be written up irrespective of outcome, and a culture encouraged whereby "success or failure" of a project is of secondary importance to the creativity and tenacity of the research. The focus should be on a quick turnaround, capitalisation where possible, and dropping of unrealisable projects, then a move on to the next good idea.

Although this report has suggested several smart materials and sensors topics that the authors consider worthy of investigation, there are many others that would certainly serve equally well in maintaining a pool of researchers able to exploit disruptive technologies in a short timeframe.

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Smart materials, Sensor systems, Disruptive technology, Integrated systems

19. ABSTRACT
Smart materials and sensor systems have made incremental advances across a broad set of Defence-related activities as materials technology continues to be developed, and a greater understanding of the underlying science gained. There is the potential for materials and sensor systems to be combined to effect a technological advantage for the Australian Defence Force in the military domain when exploited. This paper discusses the potential of these materials and systems to affect these changes, and addresses the expected future directions of the technology and systems research areas in the Advanced Materials and Sensor Systems Branch (AMSS) within Maritime Platforms Division (MPD) and the Defence Science and Technology Organisation (DSTO) as a whole. It will also provide guidance for the forward research program.